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ON MODELLING SURFACE WAVES AND VERTICAL MIXING IN THE BALTIC SEA

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Abstract

The modelling of surface waves and vertical mixing in the northern Baltic Sea is a complicated task, in which taking into account the specific features of the area is essential. The seasonal ice conditions affect the wave climate of the northern Baltic Sea and the formulation of the wave statistics. Five different ways of formulating statistics in seasonally ice-covered seas were presented, and the differences between them in the mean values and the exceedance probabilities of significant wave height were evaluated based on six years of wave hindcasts. The severest wave climate was in the Baltic Proper, where the hindcast maximum value of significant wave height was 9.7 m. The highest values were reached in autumn and winter, spring and summer had considerably less severe wave climate. Due to the irregular shoreline and archipelago, the coastal areas of Finland are mostly well sheltered from the more severe wave conditions of the open sea. Modelling of wave conditions in these areas requires high-resolution grids with sufficiently accurate description of bathymetry and land-sea mask. The manual and automated methods developed for compiling representative model grids in archipelago areas were shown to improve the accuracy of wave modelling. Taking the sheltering effects of the coastal archipelago into account on a sub-grid scale by using additional grid obstructions was shown to result in sufficient accuracy in the modelled significant wave height even when a coarser resolution was applied. However, additional measures are needed to take into account wave refraction and depth-induced wave breaking on a sub-grid scale. The different factors affecting the accuracy of the wave and hydrodynamic modelling, such as the initial and boundary conditions, bathymetry, horizontal and vertical resolution and numerical solutions, make it difficult to distinguish a specific reason behind the modelling inaccuracies. It was shown, however, that the meteorological forcing plays a key role in all marine modelling applications in the Baltic Sea, and special emphasis should be given to the production of meteorological datasets with high quality and resolution. Increasing computational resources allow us to use more exact numerical solutions, e.g., in the nonlinear four-wave interaction source term of the wave model, thus improving the accuracy of the model results. To better describe the ocean surface layer dynamics there is an evident need for coupled models and inclusion of the effect of surface waves in the modelling of marine systems. The different parametrisations of vertical turbulence used in modelling 3D hydrodynamics in the Gulf of Finland were shown to underestimate the thermocline depth and to show less steep temperature gradients than those of the measured profiles. The role of surface waves in the vertical mixing in the Gulf of Finland was studied by calculating the turbulent Langmuir numbers based on wave hindcasts. In summer the hindcast values of the turbulent Langmuir number were within the interval where the Langmuir circulation is estimated to play a role in the turbulence production together with the wind-induced mean shear. In general, a coupled 3D hydrodynamic-wave-ice model might further improve our ability to simulate short and long-term changes in the marine systems of the Baltic Sea.

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Nimeke

Aallokon ja pystysuuntaisen sekoittumisen mallinnusta Itämerellä

Tiivistelmä

Itämeren erityispiirteet tekevät aallokon ja meren pintakerroksen pystysuuntaisen sekoittumisen mallinnuksesta haastavaa. Itämeren pohjoisosat jäätyvät joka talvi ja ankarina jäätalvina jääpeite kattaa suuren osan Itämerta. Jotta merimalleilla saadaan riittävän tarkkoja ennusteita, täytyy jääpeite ottaa huomioon mallinnuksessa. Kausittainen jääpeite vaikuttaa aalto-olosuhteisiin ja aaltotilastojen tekemiseen. Tutkimuksessa esitettiin viisi erilaista tapaa tehdä aaltotilastoja kausittain jään peittämillä merialuilla sekä arvioitiin niiden tuottamia eroja merkitsevän aallonkorkeuden keskiarvoissa ja ylittymistodennäköisyyksissä. Aaltomallilaskelmiin perustuvien tilastojen mukaan ankarin aaltoilmasto on varsinaisella Itämerellä. Varsinaisen Itämeren pohjoisosissa aaltomallin laskema suurin merkitsevä aallonkorkeus oli 9.7 m. Syksyllä ja talvella aalto-olosuhteet ovat ankarammat kuin keväällä ja kesällä. Itämeren pohjoisosien rikkonainen rantaviiva ja saaristo suojaavat rannikkoalueita avomerialueiden ankarammilta aalto-olosuhteilta. Jotta saariston ja rikkonaisen rantaviivan vaikutus aallokon energian pienenemiselle pystytään mallilaskelmissa huomioimaan, täytyy aaltomallissa käyttää tiheän erottelukyvyn hilaa. Usein kuitenkin operatiivisille ennusteille asetettujen aikarajoitteiden vuoksi on malleissa käytettävä karkeampaa erottelukykyä. Tutkimuksessa käytetyt menetelmät, joilla pystytään huomioimaan erottelukykyä pienempien saarten vaikutus aallokon energian kulkeutumiseen, paransivat ennustetarkkuutta karkeampaa erottelukykyä käytettäessä. Tutkimuksessa huomattiin myös tarve kehittää lisämenetelmiä, joilla pystytään huomioimaan aallokon vaimeneminen ja taittuminen mallin erottelukykyä pienemmän skaalan syvyysvaihteluiden johdosta. Tutkimuksessa selvitettiin malleissa käytettyjen alku- ja reunaehtojen sekä erilaisten numeeristen menetelmien vaikutusta mallien ennustetarkkuuteen. Koska mallien tarkkuuteen vaikuttavat useat tekijät, on usein hankalaa löytää yhtä yksittäistä syytä mallin epätarkkuuksiin. Tutkimuksessa todettiin kuitenkin, että mallien käyttämän sääsyötteen tarkkuudella oli huomattava vaikutus merimallien ennustetarkkuuteen. Tulevaisuudessa tulisi kiinnittää erityishuomiota riittävän tarkan, ajallisesti sekä alueellisesti kattavan sääsyötteen tuottamiseksi merimallien käyttöön Itämerellä. Laskentakapasiteetin kasvu saattaa tulevaisuudessa mahdollistaa tarkempien numeeristen menetelmien käytön esimerkiksi aaltojen välisten epälineaaristen vuorovaikutusten laskennassa ja näin parantaa mallien ennustetarkkuutta. Jotta meren pintakerroksen dynamiikka pystyttäisiin jatkossa mallintamaan tarkemmin tulisi aallokon vaikutus pintakerroksen sekoittumiseen ottaa huomioon. Tutkimuksessa havaittiin, että Suomenlahdella hydrodynaamisessa merimallissa käytetyt pystysuuntaisen turbulenttisen sekoittumisen parametrisoinnit aliarvioivat lämpötilan harppauskerroksen syvyyttä. Aallokon osuutta pystysuuntaiseen turbulenttiseen sekoittumiseen Langmuirin virtauksen kautta arvioitiin Suomenlahdella perustuen aaltomallilaskelmiin. Mallilaskelmien perusteella Langmuirin virtaussoluilla saattaa olla huomattava osuus meren pintakerroksen sekoittumisessa tuulen aiheuttaman leikkausjännityksen ohella. Mallien ennustetarkkuuden parantamiseksi tulevaisuudessa päähuomio tulisi kiinnittää kytkettyjen aalto-jää-merimallien kehittämiseen.

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Preface

On the fourth year of my undergraduate studies in quaternary geology I applied for a job at the Finnish Institute of Marine Research and so begun my career as a physical oceanographer. Although it has not always been a bed of roses, I have never regretted my choice of career. I would like to thank Professor Kimmo Kahma, who decided to give me an opportunity back then, for guiding me into the interesting world of ocean surface waves in his inspiring way and for acting as my supervisor. I'm grateful to Dr. Heidi Pettersson, my co-supervisor, for her support and for being a reliable senior colleague and the head of our research group during these years. I would like to express my deepest gratitude to Dr. Kai Myrberg for his time and guidance, and for gently pushing me to wrap up my thesis.

I have had a privilege to work at three institutes, the former Finnish Institute of Marine Research, the Finnish Meteorological Institute and the Finnish Environment Institute, while conducting my studies. I would like to thank my coauthors for their contribution and for the interesting discussions we've had. I'm grateful to Dr. Carl Fortelius for sharing his expertise in atmospheric modelling and for his enthusiastic way of responding to my ideas of new modelling studies. Many thanks to Kimmo Tikka for patiently providing me new versions of bathymetries and land-sea masks. Jan-Victor Björkqvist is acknowledged for refining and programming my thoughts on grid construction in archipelago areas to a functional and modifiable program. I would like to thank Jouni Vainio for providing me data and figures of the Baltic Sea ice conditions. Pekka Alenius is thanked for sharing his knowledge on the drift of objects and brightening my workdays with stories of how the marine research has been conducted throughout the years. Tuomas Niskanen is acknowledged for making programs for handling of altimeter wave data. I'm thankful for my fellow PhD students for the support and ideas we have exchanged during lunches, seminars and meetings. There are many colleagues, who I have not mentioned by name, who have had an important role in creating an inspiring working atmosphere and who have offered me help when needed. Please know how much I appreciate your contribution.

I would like to thank Professor Matti Leppäranta for swiftly handling all the bureaucracy related to my dissertation so I could concentrate on the essentials. Dr. Ülo Suursaar and Dr. Loreta Kelpšaitė, the pre-examiners of my thesis, are thanked for their constructive comments on my work.

I would like to thank my parents Tuula and Pertti for their unfailing love and support at every turn of my life and career. Thank you to my sister Paula and brother Erno and their families for regularly offering me a refuge from the world of marine modelling. My dear friends, thank you for the interesting discussions on various scientific and non-scientific issues, and for letting me share my anxieties.

Finally I would like to thank my godchildren Joel, Pyry and Kaari for helping me to see the small wonders of the world and for constantly reminding me that, in addition to ocean surface waves, there are also other important things in life, such as sledding, playing hide and seek and eating ice cream.

Helsinki, February 2014
Laura Tuomi

Contents

List of orginal publications

I Tuomi, L., Kahma, K.K. and Pettersson, H. 2011. Wave hindcast statistics in the seasonally ice-covered Baltic Sea. Boreal Environment Research, 16:451–472.

II Tuomi, L., Kahma, K.K. and Fortelius, C. 2012: Modelling fetch-limited wave growth from an irregular shoreline. Journal of Marine Systems,105–108:96–105.

III Tuomi, L., Myrberg, K. and Lehmann, A. 2012. The performance of the parameterisations of vertical turbulence in the 3D modelling of hydrodynamics in the Baltic Sea. Continental Shelf Research, 50–51:64–79.

IV Tuomi, L., Pettersson, H., Fortelius, C., Tikka, K., Björkqvist, J.-V. and Kahma, K.K. 2014, Wave modelling in archipelagos. Coastal Engineering, 83:205–220.

Authors contribution

In paper I the author is responsible for the wave modelling, and for a large part of the data analysis and writing. In paper II the author is responsible for the wave modelling, and most of the data analysis and writing. In paper III the author is responsible for the modelling, data analysis and for a large part of the writing. In paper IV the author is responsible for most of the wave modelling, data-analysis and writing.

1 Introduction

1.1 The dynamics of the ocean surface layer

The interaction between the atmosphere and the ocean occurs in the form of the exchange of energy by heat, moisture and momentum. Excluding the near-surface viscous and molecular sub-layers, the exchange processes are dominated by turbulent motion. The momentum transfer from atmosphere to ocean drives the surface waves and surface currents, and enhances mixing in the surface layer. The growth of ocean surface waves is mainly controlled by the wind speed, fetch and duration of the wind event. The wave field is typically a combination of waves with different heights, lengths and propagation directions, and can be described with a wave energy spectrum.

The surface waves play an important part in the transfer of momentum from the atmosphere to the ocean. The momentum flux from the atmosphere contributes both to surface waves and to ocean currents. The waves retain only a small part of the momentum while the rest is transferred further into the upper ocean, e.g., through wave breaking. The surface wave breaking also generates additional turbulence and mixing in the ocean surface layer (e.g. Terray et al., 1996, Kantha and Clayson, 2004, Weber, 2008).

Ocean surface waves cause circular particle motion in the water column (Fig. 1.1). The radius of the circular motion decreases with depth, and vertical motion is negligible at water depths of more than half of the wave length. At depths of less than half of the wave length the circular motion becomes ellipsoidal, and the waves start to interact with the sea floor. The interaction becomes significant when the water depth is ca. a quarter of the wave length. The interaction between the waves and the sea bottom can release bottom sediments and enable their further transport by bottom currents.

The motion of particles does not occur along closed circular paths. In reality there is a small horizontal net transfer in the wave propagation direction. This forward motion is called the Stokes drift (Stokes, 1847). The Stokes drift together with the surface currents and winds influence the horizontal transport of particles in the surface layer. Furthermore, the Stokes drift together with the wind-induced mean shear create a Langmuir circulation (Langmuir, 1938). Langmuir circulation consists of pairs of counter-rotating rolls with their axes typically aligned with the wind direction (Fig. 1.1). Vertically the effects of the Langmuir circulation may extent down to the first significant density gradient in the water column (e.g. Leibovich, 1983). The Langmuir circulation enhances the mixing in the surface layer and has been shown to have an effect on the deepening of the seasonal thermocline (e.g. Li and Garrett, 1997, Kukulka et al., 2010).

In ice-covered seas there is one additional factor in the interaction between the atmosphere and the ocean. The ice forms a lid on the surface and changes the exchange of heat, moisture and momentum between the atmosphere and the ocean. The ice cover changes the fetch over which the waves grow and affects also the propagation of the surface waves. Short waves are rapidly attenuated by the ice field, but long waves can propagate further into the ice field and alter the distribution of sea ice as well as cause fragmentation of the ice field (e.g. Squire et al., 1995). A fragmented ice cover is more exposed to the effects of wind, waves and surface currents. In the Arctic, the recent reductions in the extent of the multi-year ice cover due to global warming enhance the surface wave action (e.g. Overeem et al., 2011). This might lead to further reduction of the ice cover due to the earlier-described processes.

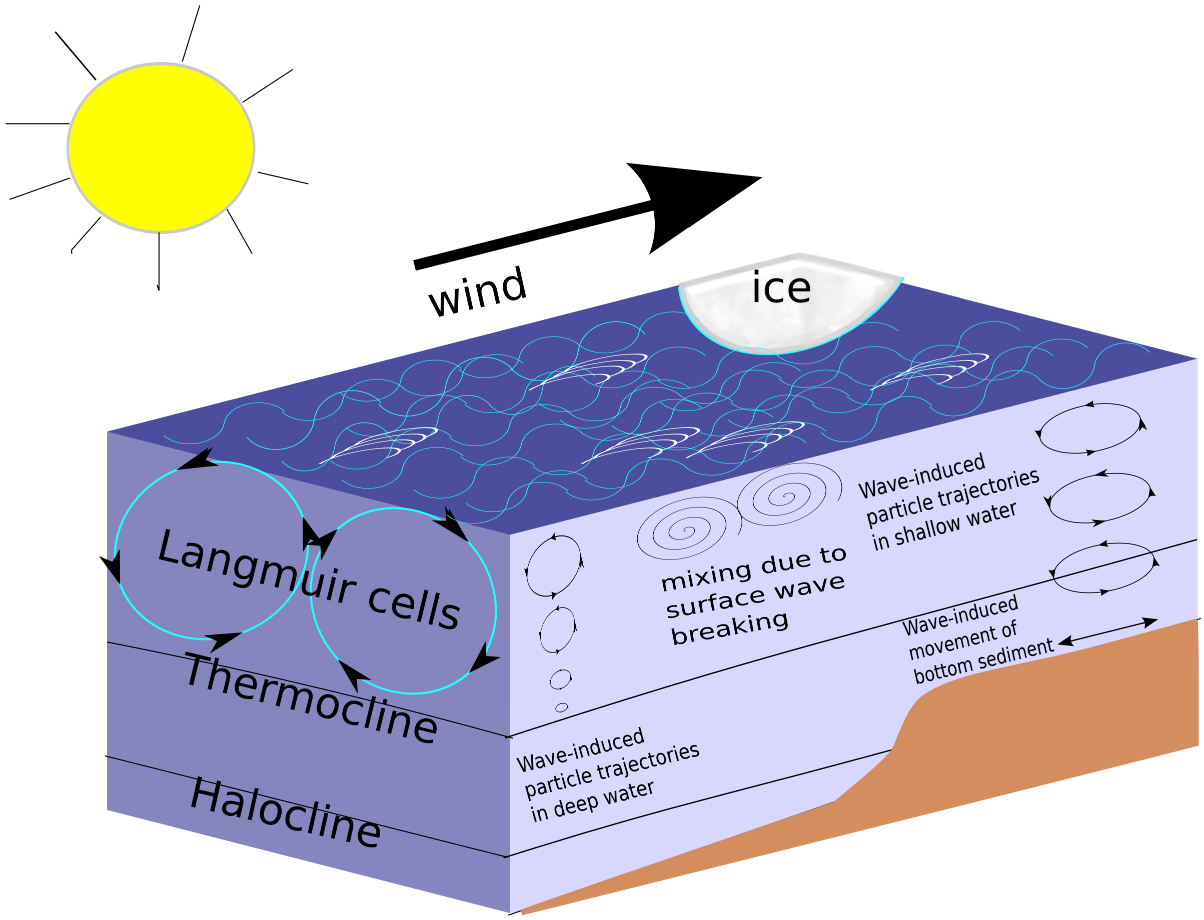

Figure 1.1: Schematic diagram representing processes related to surface waves and vertical mixing.

1.2 The Baltic Sea

When compared to the world's oceans, the Baltic Sea has several specific features that need to be taken into account when measuring and modelling its marine system. The relatively small size and complex shape of the area, the irregular shorelines in the northern part of the Baltic Sea, the limited water exchange between the North Sea and the Baltic Sea and the voluminous river runoff together make the Baltic Sea a unique environment for marine modelling.

1.2.1 Bathymetry

The Baltic Sea is a relatively small semi-enclosed basin, with a surface area of ca. 392 000 km^2 (excluding the Kattegat) (see e.g. Leppäranta and Myrberg, 2009). It is divided into several sub-basins; the largest sub-basins are the Baltic Proper (BP), the Gulf of Bothnia (GoB), the Gulf of Finland (GoF) and the Gulf of Riga (GoR) (Fig. 1.2). The Baltic Sea is connected to the North Sea through the shallow Danish Straits.

The rugged sea floor of the Baltic Sea results in intricate bathymetry. The Baltic Sea is relatively shallow with a mean depth of only 54 m. The deepest location in the Baltic Sea, the Landsort Deep, has a depth of 459 m. Similar, although not so large, differences between the mean depth and the largest depth are found in most of the sub-basins. For

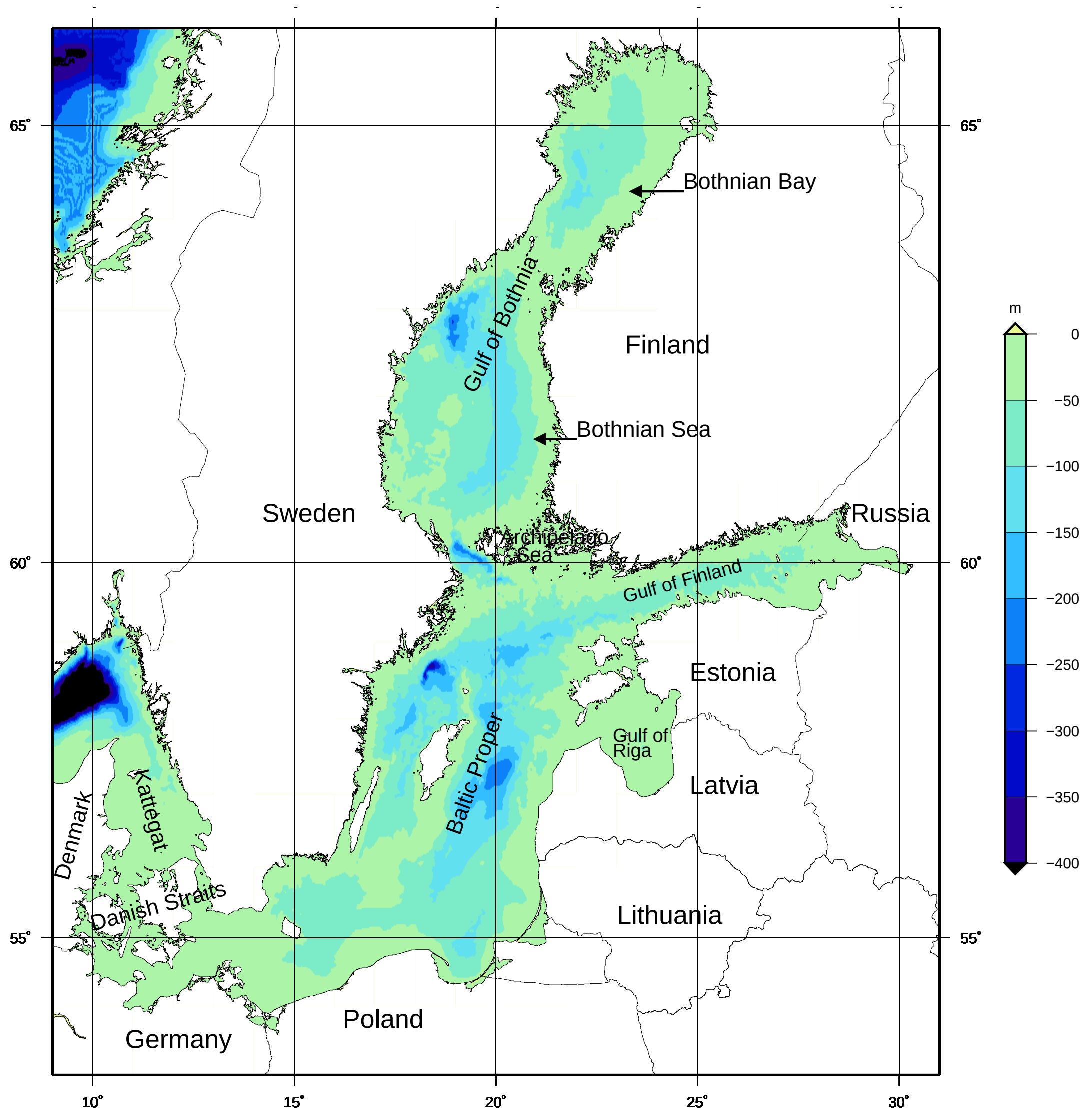

Figure 1.2: Bathymetry of the Baltic Sea based on bathymetric data by Seifert et al. (2001) with a 1 nmi resolution. The locations of the sub-basins of the Baltic Sea discussed in this thesis and the countries surrounding the Baltic Sea are shown.

example, the Archipelago Sea (ArchS), located between the GoB and BP, has a mean depth of 23 m (Suominen et al., 2010), but there are fault lines in the area some of which are deeper than 100 m. The steep slopes result in sharp gradients in the bathymetry, and to describe these with sufficient accuracy the bathymetry needs to have a high resolution.

1.2.2 Shoreline structure

The characteristics of the Baltic Sea shorelines have large areal variability due to the different geological regimes of the Baltic Sea (e.g. Winterhalter et al., 1981). To mention a few descriptive examples, the southern Baltic Sea has a smooth, low-laying coast with long sandy shorelines as a result of the Pleistocene glaciation. The Estonian coasts are characterised by escarpments of Cambrian-Ordovician rocks. The Finnish coasts and the northern part of the Swedish coast have dissected shorelines as a result of the combined processes of glaciation, glacial retreat and post-glacial rebound on the hard Precambrian bedrock.

The post-glacial rebound has modified the bathymetry and shorelines of the Baltic Sea in time. The current magnitude of the rebound varies from 0 mm/yr in the southern Baltic Sea to 9 mm/yr in the northern GoB. This has an effect e.g. on coastal dynamics. With shallower water depths some sedimentation bottoms might be more exposed to wave action. In addition, when making future scenarios for the sea level changes in the Baltic Sea, the balance between the eustatic sea level rise and land uplift (e.g. Johansson et al., 2014) needs to be taken into account.

In the northern part of the Baltic Sea the shorelines have an irregular structure and are characterized by countless small islands. Of the total length of the Finnish shoreline, 6300 km consists of that of the mainland and 39 000 km that of the islands (e.g. Granö et al., 1999). Furthermore, the total number of islands along the Finnish shoreline is over 73 000, of which ca. 40 000 are located in the ArchS. This sets strict requirements for the horizontal resolution of marine models when the area of modelling interest is in the coastal zone.

1.2.3 Specific features of the Baltic Sea physics

The Baltic Sea physics has several specific features that need special attention whenever carrying out modelling studies. The limited exchange of water between the Baltic Sea and the North Sea through the shallow and narrow Danish Straits, together with the voluminous river runoff, make the Baltic Sea a brackish water basin. The halocline and seasonal thermocline are typically situated at different depths. There are also areas where the halocline is completely missing (e.g., areas behind sills, shallow areas, and the river mouths of the most voluminous rivers), and there the stratification is determined mainly by the seasonal thermocline. The horizontal gradient in the surface salinity is large, the salinity being highest at the southern Baltic Sea close to the Danish Straits (over 14 psu) and lowest in the northern extremity of the GoB and the eastern extremity of the GoF (less than 3 psu). This results in extremely complicated stratification conditions, compared to the oceans causing a challenge to, e.g., the parametrisation of vertical turbulence. A comprehensive summary of the vertical mixing processes in the Baltic Sea can be found in Reissmann et al. (2009).

The small size and water volume of the Baltic Sea affects its physics considerably. The tides are small, of the order of only a few centimetres, and short-term sea level variations are mainly due to meteorological forcing. The wave climate of the Baltic Sea is less severe than, e.g., that of the North Atlantic, and the wave field in high wind situations is typically fetch-limited. Also the geometry of the Baltic Sea affects the evolution of the wave field and, e.g., in the Gulf of Finland the waves are steered towards the axis of the gulf (Pettersson et al., 2010). Due to the large variability in the meteorological conditions the long-term mean circulation is weak and the currents are damped considerably due to the small size of the basins. The main mechanism inducing the currents in the Baltic Sea is wind stress. The other effects, the thermohaline density gradient, the surface pressure gradient and tidal forces, are usually considerably smaller. The internal Rossby radius, a length scale defining the size of mesoscale eddies, is small in the Baltic Sea. In the Gulf of Finland, the mean value of the internal Rossby radius in the shallower areas (depth < 36 m) is ca. 2.1 km and in deeper areas 4.1 km (Alenius et al., 2003). In order for a hydrodynamic model to be able to solve the eddies, the horizontal resolution of the model grid should be smaller than the internal Rossby radius. However, this is not always achievable, due to the restrictions on computational resources.

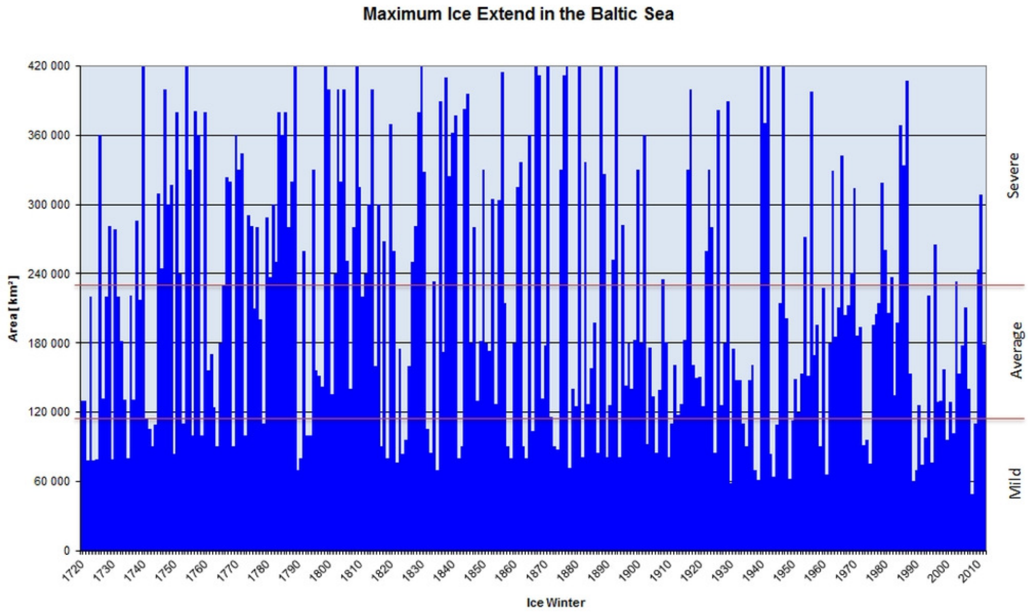

Figure 1.3: Maximum ice extent in the Baltic Sea in 1720–2012. (Redrawn from Vainio et al. (2012), courtesy of Mr. Jouni Vainio, FMI.)

The Baltic Sea freezes annually. Typically, the ice season starts in November, when the coastal areas of the Bothnian Bay begin to have an ice cover. The maximum ice extent of the Baltic Sea varies from year to year (Fig. 1.3). In the severest winters almost the whole Baltic Sea has an ice cover, and even in the mildest winters there is ice in the GoB and in the eastern part of the GoF. The ice season lasts until May or even early June.

1.3 Why marine modelling is needed in the Baltic Sea

The need for marine modelling applications has increased in the past few decades. In-situ measurements, however intensive, only cover certain temporal and spatial dimensions. In addition to the evident basic research needs, models are needed to fill in these gaps, and more importantly, to give projections of future conditions of the Baltic Sea in the short and long term.

1.3.1 Marine safety

Marine traffic has been steadily increasing in the Baltic Sea. On an average, 2000 ships visit the Baltic Sea each day, and estimates of the increase in maritime transportation indicate that this will be doubled by 2017 (e.g. HELCOM, 2013). Sufficient knowledge of the sea state, marine weather and ice conditions through an adequately dense observational network, together with reliable forecasts, are essential for shipping and safety at sea. The highest measured significant wave height in the Baltic Sea is 8.2 m, measured by the northern Baltic Proper (NBP) wave buoy, and even higher significant wave heights have been simulated by wave models for areas or time periods for which no measured data are available (paper I). The authorities need to have functional systems to give warnings of severe wave conditions, predict the drift of harmful substances, such as oil or toxic and radioactive substances, and to assist the marine rescue service in marine accident situations. In this, modelling plays a key role and there is a need for further development of the existing marine forecasting systems in order to increase the accuracy of the forecasts.

1.3.2 Coastal and offshore construction and maritime spatial planning

The design of coastal and offshore structures requires estimates of the conditions they will face during their lifetime. These estimates can be based on measured data or, if these are not available, on modelled values. The observational network is relatively sparse, and often modelling is the best tool available to estimate the loads of wind, ice, waves and fluctuations of sea level on structures.

The construction of coastal and offshore structures may induce changes in the current and wave fields. These changes may in turn induce changes, e.g., in sediment transport and salinity and temperature fields in the area. Evaluation of the environmental impact of large construction projects in coastal and offshore areas requires modelling applications with a high spatial resolution. Also, maritime spatial planning and the implementation of the Marine Strategy Framework Directive (MSFD) require the monitoring of the current status of, and future changes in, the hydrographic and wave conditions.

For the design of new fairways, especially in the coastal areas, knowledge of the wave conditions is beneficial. This information may be used to find a route that is sheltered from the more severe wave conditions of the open sea. Furthermore, due to the rugged seafloor of the northern Baltic Sea, there are plenty of shoals in the coastal areas; these may cause wave refraction and concentration of wave energy, and thus cause an unnecessary safety risk to vessels travelling in the close vicinity of such areas. In addition to this, the identification of risks that marine transport may propose for the marine environment, e.g. in the form of pollution from marine accidents, has led to suggestions for planning optimal fairways minimising the risk of environmental pollution reaching the most vulnerable areas (e.g. Soomere et al., 2011, Soomere and Quak, 2013, Lehmann et al., 2014).

1.3.3 Eutrophication

Eutrophication, arising from the extensive input of nutrients due to past and present human activities, has dramatically affected the fragile ecosystem of the Baltic Sea. Although there have been reductions in the nutrient loads, e.g., due to improvements in waste-water treatment, the condition of the Baltic Sea has not improved as fast as hoped, and there is a need for further actions. The Helsinki Commission (HELCOM) has initiated the Baltic Sea Action Plan (BSAP) in order to restore the good ecological status of the Baltic Sea by the year 2021. The BSAP proposes country-wise reductions of nutrient loads of phosphorus and nitrogen in order to reach the target. In addition to this, implementation of the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) is under way. In order to assist decision-making, there is a need for monitoring of the present state of the Baltic Sea together with projections of the current actions on the future state of the Baltic Sea using models.

Although present biogeochemical models have been shown to have benefited decision-making, their use still requires a significant amount of expert evaluation of the results (e.g. Hyytiäinen et al., 2012), as well as additional methods to improve the results, before they can be utilised (Vanhatalo et al., 2013). To simulate the marine system in sufficient detail, the interaction between the atmosphere, surface waves, marine hydrodynamics, ice and biogeochemistry needs to be modelled as an entire system. At present, the modelling is typically done with individual model components that utilise the data calculated by another model as boundary conditions (meteorological forcing, current field, ice field). Although the modelling of the basic parameters, such as the sea surface temperature (SST) or significant wave height (H_s), can be done with a relatively good accuracy using this approach, coupled models are needed to improve the description of processes e.g. in the air-sea interface and in the ocean surface layer. Additionally, the accuracy of the basic parameters, such as SST and H_s can be improved when coupled model systems are used (e.g. Janssen et al., 2001, Järvenoja and Tuomi, 2002, Janssen, 2012).

1.4 Outline and aim of this study

In this thesis the effect of the specific conditions of the Baltic Sea on the modelling of the surface waves and vertical mixing in open sea areas (papers I and III) and surface waves in coastal areas (papers II and IV) are studied. In Chapter 2 the models used in this thesis and the relevant boundary and initial conditions are introduced. In Chapter 3 different ways to formulate wave statistics in seasonally ice-covered seas (paper I) are discussed, and the wave conditions in the open sea areas (paper I) and coastal areas (papers II and II) of the northern Baltic Sea are presented. In Chapter 4 the effects that meteorological forcing (papers I, II, III and IV), the horizontal resolution and the bathymetry (papers II and IV) have on the modelled parameters are discussed. Furthermore, the numerical solutions used in the models (papers II and III with some additional analysis) and their effect on the accuracy of the model results are studied. Chapter 5 discusses the need for coupled models in the Baltic Sea, and presents an estimate of the role that surface waves might have in the dynamics of the surface mixed layer through Langmuir circulation in the Gulf of Finland. This is followed by conclusions in Chapter 6.

The topics discussed in this thesis can be summarised into the following points:

1. Discuss different ways to formulate wave statistics in the seasonally ice-covered Baltic Sea and study the differences in the resulting wave climate.

2. Study the wave climate of the northern Baltic Sea based on verified wave hindcasts and discuss the effect of seasonal ice conditions on mean values, exceedance probabilities and maximum values of the significant wave height.

3. Study the wave conditions in the coastal areas of Finland based on wave model hindcasts.

4. Evaluate the accuracy of different meteorological datasets available for the Baltic Sea and discuss their suitability for marine modelling.

5. Study how the implementation of a model affects the accuracy of the modelled parameters in the Baltic Sea. Special emphasis is given to horizontal resolution, bathymetry, initial conditions and seasonal ice-cover.

6. Study how the approximations made in the numerical solutions of the wave model source terms affect the accuracy of the modelled growth of wave energy and the shape of the wave spectrum.

7. Study the accuracy of different parametrisations of vertical turbulence in the modelling of 3D hydrodynamics in the Gulf of Finland, and evaluate the role that surface-wave-induced processes have on the mixing in the sea surface layer through Langmuir circulation.

8. Discuss the need for the coupled modelling of surface waves, ice, and 3D hydrodynamics in the Baltic Sea in order to produce more accurate predictions of the surface drift, vertical mixing and wave-ice interaction.

2 Modelling

Nowadays there are several models available and applicable for the modelling of surface waves and 3D hydrodynamics in the Baltic Sea. Each model has different capabilities and advantages depending on the numerical solutions and parametrisation used when building the model. In the intercomparison study of six hydrodynamic models implemented in the Baltic Sea area (Myrberg et al., 2010), all the models managed to reproduce the general features of the surface temperature and salinity. However, the models showed different skill in predicting these parameters in the different areas of the GoF. The appropriate selection of a model depends on several factors, e.g., the task for which the model is used, familiarity with the model and its prior performance, technical details (e.g. the possibility of parallel computing, or using grid nesting) and the numerical solutions employed in the models.

In papers I, II and IV wave modelling was carried out using the wave model WAM (WAMDI, 1988, Komen et al., 1994, Monbaliu et al., 2000). WAM is under continuous development by an international group of scientists (the version of the code used in papers I, II and IV is given in Table 2.1). The first implementation used at the Finnish Institute of Marine Research (FIMR, now at the Finnish Meteorological Institute, FMI) was made in co-operation with the European Centre of Medium-Range Weather Forecasts (ECMWF) in the 1990's. The first operational version of WAM was brought into use at FIMR in 2001. It was run as part of the coupled atmosphere-wave model operational at that time at FMI and FIMR (Järvenoja and Tuomi, 2002). A detailed description of WAM and the applications of the model used in this thesis are given in section 2.1.

The 3D hydrodynamic model COHERENS (Luyten et al., 1999) was used in the modelling study of vertical turbulence parametrisations presented in paper III. The implementation of the COHERENS model for the Baltic Sea was done by the National Environmental Research Institute (NERI) in Denmark. This implementation was utilised together by NERI and the Finnish Environment Institute (SYKE) during the Eutrophication-MAPS project (Myrberg et al., 2010). It was further used in paper III to study the effect of different turbulence parametrisation schemes on vertical mixing in the Baltic Sea. COHERENS is a good choice for this kind of study, since it contains several alternative vertical turbulence schemes. A description of COHERENS is given in section 2.2.

To implement a model for the Baltic Sea is a complicated task, and has to be done taking into account the specific features of the Baltic Sea (cf. section 1.2). The appropriate choice of grid resolution depends on several factors, which will be further discussed in sections 2.5 and 4.2. The accuracy of the input and boundary conditions is important in the hydrodynamic modelling of the Baltic Sea. Also using the appropriate wind forcing with a sufficiently high resolution and accuracy is essential for marine modelling.

2.1 The WAM wave model

WAM is a third-generation[1] wave model (WAMDI, 1988, Komen et al., 1994, Monbaliu et al., 2000) that calculates the evolution of the wave energy spectrum through the action balance equation (given here in spherical coordinates)

[1]Third-generation wave models allow the wave spectrum to evolve with no assumptions as to the form of the spectrum (up to the cut-off frequency).

$$\frac{\partial N}{\partial t}+(cos\phi)^{-1}\frac{\partial}{\partial\phi}(\dot{\phi}cos\phi N)+\frac{\partial}{\partial\lambda}(\dot{\lambda}N)+\frac{\partial}{\partial\omega}(\dot{\omega}N)+\frac{\partial}{\partial\theta}(\dot{\theta}N)=S_{in}+S_{ds}+S_{nl}+S_{bt}+S_{wbr} \tag{2.1}$$

where N is the action density, t is time, ω is the angular velocity, θ is the wave propagation direction, ϕ is the latitude and λ is the longitude. The action density is defined as $N = F/\sigma$, where F the energy density of the spectrum representing the distribution of wave energy over frequencies and propagation directions and σ is the so-called intrinsic frequency

$$\sigma = \sqrt{gktanh(kh)} \tag{2.2}$$

where k is the wave number, h the water depth and g the acceleration due to gravity

$$\dot{\phi} = (c_g cos\theta - \mathbf{U}_c|_{north})R^{-1} \tag{2.3}$$

where c_g is the group velocity, R is the radius of the Earth and $\mathbf{U}_c$ is the surface current given in northerly and easterly directions.

$$\dot{\lambda} = (c_g sin\theta - \mathbf{U}_c|_{east})(Rcos\phi)^{-1} \tag{2.4}$$

$$\dot{\theta} = c_g sin\theta tan\phi R^{-1} + \dot{\theta}_D \tag{2.5}$$

$$\dot{\omega} = \frac{\partial\Omega}{\partial t} \tag{2.6}$$

$$\dot{\theta}_D = \left(sin\theta\frac{\partial\Omega}{\partial\phi} - \frac{cos\theta}{cos\phi}\frac{\partial\Omega}{\partial\lambda}\right)(kR)^{-1} \tag{2.7}$$

where

$$\Omega = \sigma + \mathbf{k}\cdot\mathbf{U}_c \tag{2.8}$$

The source terms in WAM cycle[2] 4 include the wind input S_{in} (Janssen, 1989), dissipation of waves due to whitecapping[3] S_{ds} (Komen et al., 1994), discrete interaction approximation of the nonlinear four-wave interactions S_{nl} (Hasselmann et al., 1985) and dissipation of waves due to bottom friction S_{bt} (Komen et al., 1994). In cycle 4.5 the dissipation of waves due to the depth-induced wave breaking S_{wbr} by Battjes and Janssen (1978) has been added. WAM uses surface wind speed and direction at a height of 10 m as forcing, and the propagation is done using a first-order upwind scheme. The model includes both deep or shallow water solutions for the equations and optionally depth- and current-induced wave refraction can be used. A method of handling ice conditions by excluding from calculation grid points, having an ice concentration of over 30%, was used in paper I. Handling of grid obstructions by the method of Tolman (2003) was implemented in WAM and used in the model studies made in paper IV.

[2] The cycle refers to the version number of the wave model.

[3] Steepness-induced breaking of surface waves in deep water occurring when the wave height becomes too large compared to the wavelength.

Table 2.1: The implementations of WAM used in papers I, II and IV.

	Paper I	**Paper II**	**Paper IV**
Model used	WAM cycle 4	WAM cycle 4.5.1	WAM cycle 4.5.1
Grid	Spherical	Spherical	Spherical
Coarse grid resolution	6 nmi	2 nmi	1 nmi
Bathymetry	IOW (Seifert et al., 2001)	IOW (Seifert et al., 2001)	ETOPO1 (Amante and Eakins, 2009)
Nested grid resolutions	-	1 nmi and 0.25 nmi	0.5 nmi and 0.1 nmi
Nested bathymetry	-	IOW and coastal nautical charts	GEBCO and coastal nautical charts
Directional resolution	15 deg	15 deg	10 deg
Frequency range	0.042 – 1.073 Hz	0.042 – 1.719 Hz	0.060 – 2.468 Hz
Wind forcing	HIRLAM	Re-analysed HIRLAM	HIRLAM and re-analysed HARMONIE
Wave refraction	Yes	Yes	Yes/No
Depth-induced wave breaking	No	No	Yes/No

2.2 The COHERENS 3D hydrodynamic model

The COHERENS 3D hydrodynamic model (Luyten et al., 1999) solves the momentum equation using the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium. The equations of momentum and continuity are solved numerically using the mode-split-up technique (see Blumberg and Mellor, 1987). Details of the Baltic Sea implementation are given in Table 2.2.

The COHERENS model has a choice of various turbulence closure schemes. The two-equation models solve the turbulent kinetic energy (k) using the dissipation rate, ϵ, (e.g. Rodi, 1984) or mixing length, l, (Mellor and Yamada, 1982) as a length scale. The k-model and algebraic schemes by Pacanowski and Philander (1981) and Munk and Anderson (1948), and flow-dependent parametrisation are also included. Stability parameters as formulated by Luyten et al. (1999), Mellor and Yamada (1982) and Munk and Anderson (1948) are available in the model. Additionally, in paper III the stability functions introduced by Canuto et al. (2001) were implemented in the model with the

Table 2.2: The Baltic Sea implementation of COHERENS used in paper III.

Horizontal grid	2 nmi spherical Arakawa C (Arakawa and Lamb, 1977)
Vertical grid	50 sigma layers
Bathymetry	Based on IOW bathymetry (Seifert et al., 2001)
2D advection	First-order upwind
3D advection	TVD surberbee scheme (Roe, 1985)
Equation of state	UNESCO (1981)
Surface parametrisations	Large and Pond (1981), Luyten et al. (1999)
Open boundary condition	Temperature, salinity and water level at Kattegat
River discharge	Monthly mean discharge of major rivers obtained from Bergström and Carlsson (1994)

formulation proposed by Burchard and Bolding (2001) to extend the analysis of the turbulence parametrisations to newer formulations of the stability functions. Additionally, a limiting condition[4] for the mixing length was applied for some of the parametrisations. For details of these parametrisations see Luyten et al. (1999) and paper III.

2.3 Meteorological forcing

The meteorological forcing needed to run the wave and hydrodynamic models in the Baltic Sea can be obtained from different sources. The forcing dataset that is most representative depends on the application and the period for which the modelling is to be carried out.

One meteorological data source based on observations in the Baltic Sea is that from the Swedish Meteorological and Hydrological Institute (SMHI). This dataset is based on data from the observational network of synoptic weather stations starting from 1970. The dataset was updated until 2012. It covers the entire Baltic Sea with 1° horizontal resolution, the temporal resolution being 3 hours for geostrophic wind speed, mean sea level pressure, air temperature, relative humidity and total cloud cover. Accumulated precipitation is given at 12-hour intervals. This dataset was used as meteorological forcing for the COHERENS model in paper III.

The operational archives of ECMWF and various national meteorological institutes' Numerical Weather Prediction (NWP) systems are adequate sources from which to construct meteorological forcing datasets. However, a common problem in these datasets

[4]The limiting condition for mixing length imposes upper limits for the stability parameters. When the limiting condition is used, the stability functions level off at a constant value when the Richardson number exceeds a critical value.

is the heterogeneous quality of the parameters due to continuous upgrades in the model physics, numerics and resolutions. However, if the verification of the derived parameter is done thoroughly, the use of these datasets can lead to sufficient accuracy, as was shown in paper I.

Re-analysed meteorological datasets provide a good bases for performing case studies on past periods. However, until recently the resolution of the re-analysed meteorological datasets, such as ERA-40 (Uppala et al., 2005), has been relatively coarse compared to the small size of the Baltic Sea. In recent years re-analysis datasets with local NWP systems have been performed for the Baltic Sea (e.g. Luhamaa et al., 2011). In paper II the surface wind field for the year 1976 was re-analysed using FMI's NWP system HIRLAM (www.hirlam.org). In paper IV a re-analysis for the Archipelago Sea for the year 2010 was made with the high-resolution (ca. 2.5 km) non-hydrostatic NWP system HARMONIE (Seity et al., 2011). The accuracy of these datasets and their usability in the model studies will be discussed later in section 4.1.

2.4 Measured datasets

2.4.1 Wave measurements

Instrumental wave measurements are available from the Baltic Sea from the beginning of the 1970's (Wahl, 1973a,b,c, Kahma, 1976). Since then, measurement campaigns have been carried out in various different locations of the Baltic Sea. Operational wave measurements started in the Baltic Sea at the end of the 1980's and are presently being carried out there by FMI, SMHI, Bundesamt für Seeschifffahrt und Hydrographie (BSH, Germany), Helmholtz-Zentrum Geesthacht (HZG, Germany) and the Marine Systems Institute (MSI, Estonia). A more thorough description of the history of Baltic Sea wave measurements is given in paper I. The wave measurements used in this thesis include those made in the Bothnian Sea in 1976 (Kahma, 1981b), in the Archipelago Sea in 2010 (a description of the measurements is given in paper IV) and data from FMI's (former FIMR) operational wave buoys (the locations of the measurement sites are shown in Fig. 2.1, upper panel).

2.4.2 Hydrographic measurements

Evaluation of the results of hydrodynamic models is typically limited by the lack of measured datasets with a sufficiently high resolution in both space and time. The monitoring stations are visited typically 3-5 times per year; even the intensive monitoring stations are rarely visited more frequently than once a month. Furthermore, the intensive monitoring stations are typically located near coastal areas and do not represent the true open sea conditions.

In 1996, a measurement campaign was carried out jointly with the Finnish research vessel Aranda and the Russian research vessel Nikolai Matusevich in the Gulf of Finland, resulting in over 300 measured temperature and salinity profiles during the period from June to August (Fig. 2.1, lower panel). This was done in connection with the Gulf of Finland Year 1996. The high temporal and spatial resolution of the measured profiles makes it an outstanding dataset for validation of the performance of hydrodynamic models in a limited area (see Myrberg et al. (2010) for details). The dataset was used to analyse the performance of vertical turbulence parametrisations in paper III.

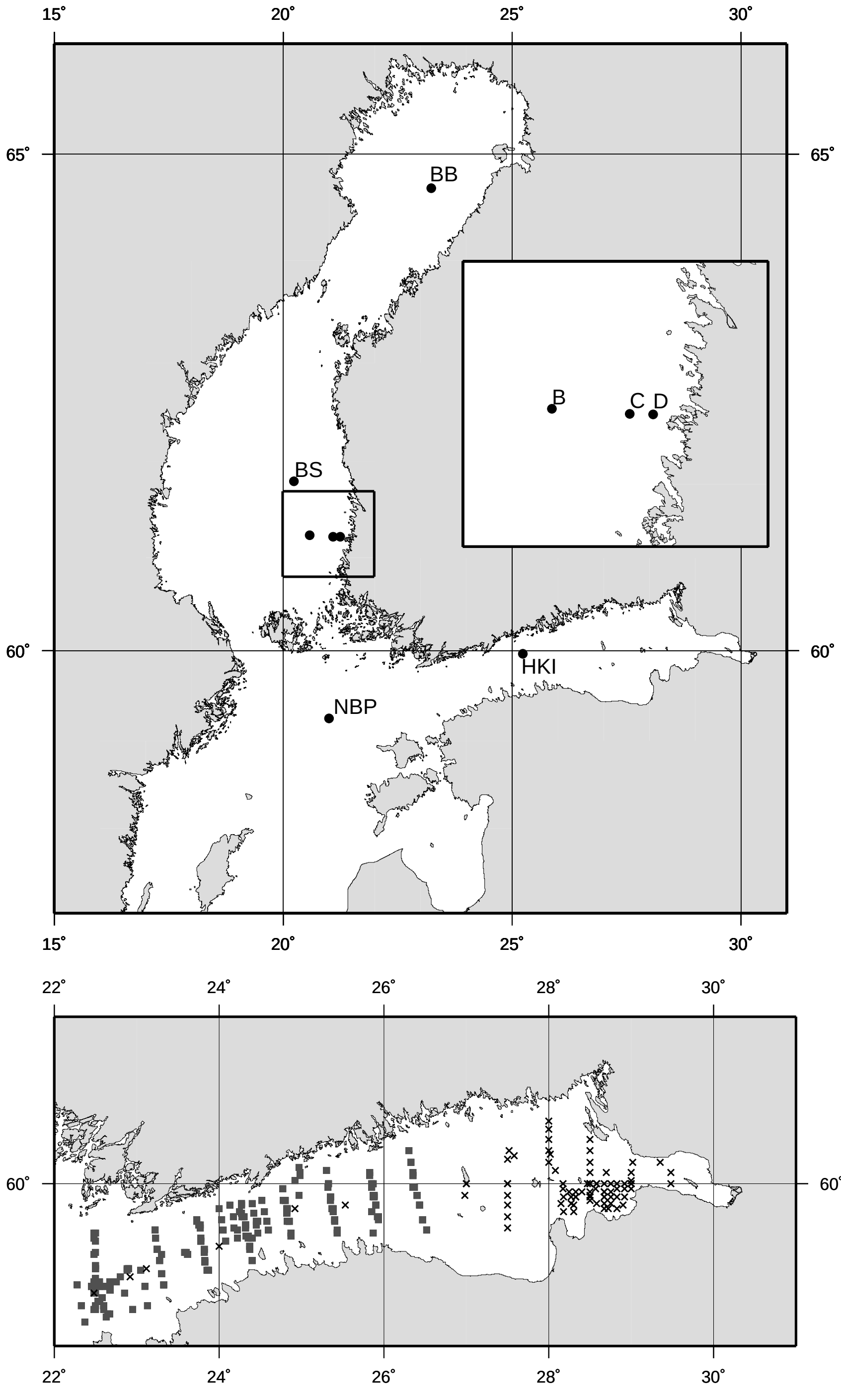

Figure 2.1: Locations of FMI's operational wave buoys in the northern Baltic Proper (NBP), in the Gulf of Finland off Helsinki (HKI), in the Bothnian Sea (BS) and in the Bothnian Bay (BB). Also shown are the locations of the buoys used in the wave measurement campaign in the Bothnian Sea in 1976 (buoys B, C and D in the close-up) (upper panel). Profiles of temperature and salinity in the Gulf of Finland were measured in 1996 by R/V Aranda (grey squares) and R/V Nikolai Matusevich (black cross) (lower panel).

2.5 Bathymetry and grid generation

Compiling a representative bathymetry for marine models in the Baltic Sea is not a trivial task. The freely-available bathymetries such as IOW (Seifert et al., 2001) or ETOPO1 (Amante and Eakins, 2009) have a resolution of 1 nmi. Such a resolution is sufficient for compiling grids for coarser resolution open sea modelling applications. However, the shoreline description in these datasets does not represent the irregular shorelines of the northern Baltic Sea with sufficient accuracy (paper II). Additional information from coastal nautical charts is needed to improve the land-sea mask[5] in the model grid.

For the wave model grids used in papers I and II, the bathymetry is based on that of the IOW with a 1 nmi resolution. When making a wave model grid, the land-sea mask has to be modified to better describe the shoreline structure in the northern Baltic Sea. For the model grids prepared for the wave model in papers I and II these modifications were made manually using the FIMR method[6]. In paper IV automated methods to create bathymetry by combining data from different sources were developed. The coastal nautical charts were used as the main source of information to create a 0.1 nmi resolution bathymetry for the Archipelago Sea area. Additional data from the General Bathymetric Chart of the Ocean (GEBCO, www.gebco.net) bathymetry with a 30 arc seconds resolution were used to fill in the gaps in the bathymetric data of the coastal nautical charts. In addition, high resolution (0.01 nmi) shoreline data were utilised to compile a land-sea mask for the model grid.

For applications which have strict time constraints, such as operational forecasts, grids with a coarser resolution are often needed. When compiling coarse resolution grids based on data from high resolution grids, the definition of land-sea mask in coastal archipelago areas is not trivial. Direct calculation of the percentage of land points in the area of the coarser grid cell is typically used, with a threshold value for the land fraction being employed to determine the land-sea mask for the coarser grid. In paper IV it was shown that direct calculation of the land points in this way led to an underestimation of the land fraction in the coarser grid, and a method was developed to take into account land areas overlapping the grid cell boundaries (the cell boundary independent method, Fig. 2.2). These methods provide different possibilities to compile grids for the modelling of the coastal archipelago areas.

Wave models are able to use additional grid obstruction to approximate, at the sub-grid scale, the effect the archipelago has on the wave field. Using grid obstruction, the energy in the wave spectra propagating from one grid cell to the next is reduced according to the obstructions (e.g. Tolman, 2003). The possibility of using additional grid obstructions in wave forecasting in the Archipelago Sea was studied in paper IV.

2.6 Initial and boundary conditions

2.6.1 Initial fields

Due to the small size of the Baltic Sea, the waves are not long-lived and therefore the spin-up period needed for a wave model is relatively short (1/2 - 1 days). For a hydrodynamic

[5] A land-sea mask describes how the model grid points are distributed between land and sea points.

[6] This method employs both information available in coastal nautical charts and also expert analysis to improve the land-sea mask in freely-available bathymetries, such as IOW or ETOPO1. A more thorough description of this method is given in paper II.

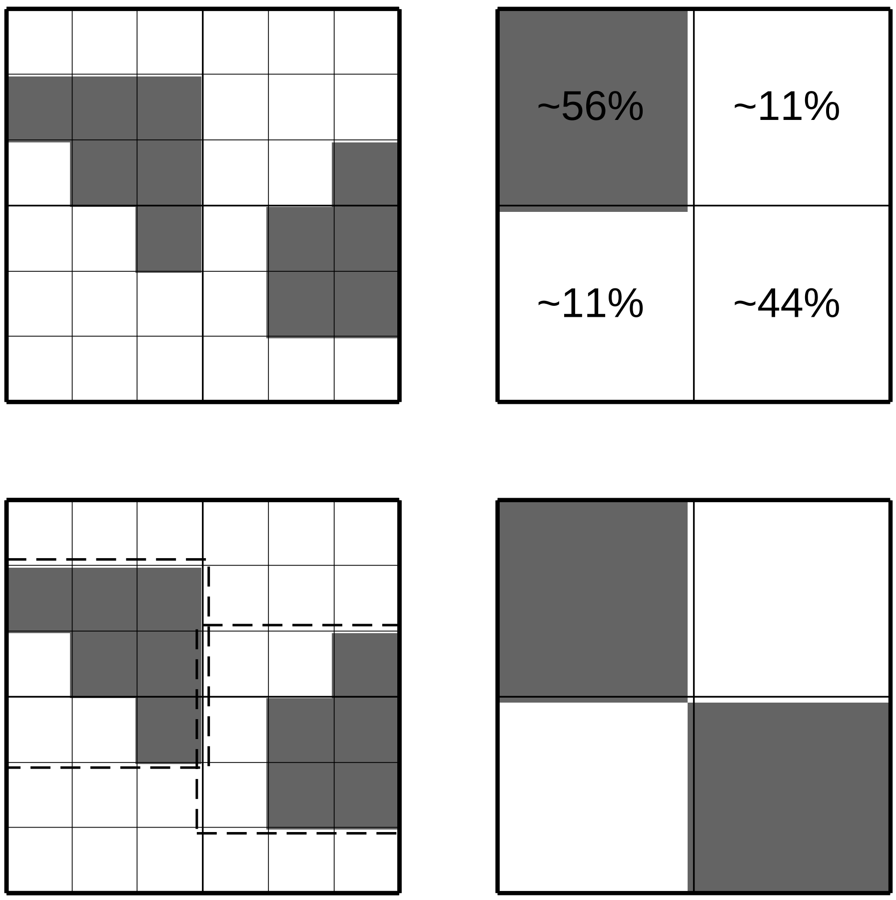

Figure 2.2: The direct method of calculating land percentage for a coarser resolution grid and the resulting land-sea mask using a threshold value of 50 % (upper right) based on the land-sea mask of the higher resolution grid (upper left, land points coloured grey and sea points white). The dashed lines in the lower left panel show the solid land areas crossing grid cell boundaries identified using a cell boundary independent method, with the resulting land-sea mask in a coarser resolution grid being shown in the lower right panel.

model, the initial conditions for salinity and temperature need to be defined, and a spin-up period of several months is needed in order to stabilise the balance between the initial conditions, river runoff and the boundary conditions (e.g. Andrejev et al., 2000). In paper III the initial conditions were based on temperature and salinity profiles measured in the Baltic Sea in January-March 1996. The Data Assimilation System developed by Sokolov et al. (1997) was used to distribute the measured data over the model grid. The accuracy of the initial conditions has a significant effect on the length of the spin-up period needed (paper III). Generally, a spin-up period of two months has been found to be sufficient in the Baltic Sea, at least for the Gulf of Finland (Andrejev et al., 2000). However, this is a complicated matter, and due to the limited spatial and temporal coverage of the measured data the interpretation of the accuracy of the model results and their relation to the initial conditions is not trivial.

2.6.2 Open boundary conditions

For a hydrodynamic model, boundary conditions at the Danish Straits are needed. There are several ways to employ open boundary conditions. In paper III the boundary conditions were provided by another 3D model, namely HIROMB (Funkquist, 2001), the area of which covers both the Baltic Sea and the North Sea.

For the wave model the open boundary in the Kattegat allows waves to propagate away from the modelling area, but no incoming waves are taken into account (this assumption is used in paper I and in papers II and IV for the basin-scale grid providing the boundary conditions for the high-resolution grids). This is a reasonable assumption, when interest is focused on the open sea areas of the Baltic Sea, excluding the Kattegat.

The high resolution wave model grids used in the northern Baltic Sea (papers II and IV) are nested inside the Baltic Sea grid, and receive boundary information in the form of wave spectra from the coarse-resolution model run.

2.6.3 Ice

In the Baltic Sea, each marine model has to have the ability to handle the seasonal ice conditions in order to produce reliable results. In the hydrodynamic models the ice conditions have to be taken into account either through parametrisations or by a separate ice module. Wave models, however, typically handle ice as a boundary condition by excluding grid points from the calculations wherever the ice concentration exceeds a certain threshold value (e.g. 30 % in paper I). This method ensures that the fetch used for the wave growth in the wave model starts from the average ice edge and that waves are not predicted for areas that have an ice cover.

In paper III the hydrodynamic modelling was done for the ice-free summer season, therefore the ice conditions were not considered in this study. For a wave model the ice concentration data can be taken from different sources, e.g., from satellite analysis, from data provided by the local Ice Service or from ice models. In paper I, ice concentrations were provided by FMI's (previously FIMR's) Ice Service. These data are available in gridded format daily during the ice season, except at the beginning of the ice season, when information is updated twice a week.

3 Modelling the Baltic Sea wave conditions

The specific features of the Baltic Sea (cf. section 1.2) affect the evolution of surface waves significantly. The small size and the geometry of the Baltic Sea limit the fetch over which the surface waves grow. Nevertheless, in the Baltic Sea waves may grow high enough to be of importance for shipping and safety at sea. Soomere et al. (2008) showed, based on verified wave model simulations, that a 9.5 m significant wave height was plausible during the Gudrun storm in January 2005. The highest significant wave height measured during this storm by the Northern Baltic Proper wave buoy was 7.7 m, at a location which is slightly off that where the highest significant wave heights were simulated by the wave models. Although such large values of significant wave height are rare in the Baltic Sea, as was shown in paper I, the accurate modelling and forecasting of such events is important.

The Baltic Sea wave climate is affected by the seasonal ice cover. As discussed earlier in sections 1.1 and 2.6.3, the ice cover reduces the fetch over which the waves grow. Also, the ice season partly coincides with the time of the year when the wind speeds are the highest. There is a high annual variability in the Baltic Sea ice conditions (Fig. 1.3) and therefore the effect of the ice conditions on the wave climate varies from year to year.

Although the wave conditions in the open sea areas of the Baltic Sea can be quite severe, the coastal areas of the northern Baltic Sea are mostly sheltered by the irregular shoreline and archipelago. These areas are also characterised by shoals that cause depth-induced breaking and refraction of waves, which may cause concentration of wave energy, and under certain conditions increase the significant wave height compared to the surrounding areas.

3.1 The formulation of wave statistics in seasonally ice-covered seas

The seasonal ice cover affects the formulation of the wave statistics. There are gaps in the measured and modelled wave datasets due to the ice-season (provided that the ice conditions have been taken into account in the wave modelling). These gaps are not randomly distributed and therefore cannot be ignored when compiling the statistics. In the case of measured data, data is typically missing both before and after the ice season, since the wave buoys have to be recovered well before there's a risk of ice. Generally, the buoys are also deployed some time after the end of the ice season. The gaps in the data due to the ice can be handled in different ways when formulating the statistics; in paper I, five different ways of formulating wave statistics in seasonally ice-covered seas were presented, based on prior work by Kahma et al. (2003).

Measurement statistics (Type M)

The statistics are calculated taking into account only the measured values. The uneven distribution of the missing values is not compensated.

Ice-time-included statistics (Type I)

In the presence of ice the significant wave height equals zero.

Ice-free time statistics (Type F)

Only the part of the year when the sea is ice-free is taken into account when the statistics are calculated.

Hypothetical "no-ice" statistics (Type N)

The statistics are calculated to represent the wave climate under the assumption that the sea remains ice-free throughout the year.

Exceedance time statistics (Type ET)

The statistics are presented as exeedance times (e.g. hours during a year instead of percentages of hours per year)

The annual mean values and exceedance probabilities (percentiles) calculated by the different types of statistics give differing results in the seasonally ice-covered seas. In the northern part of the Baltic Sea, the largest differences in the annual mean values of significant wave height calculated by type I, F and N statistics are in the Bothnian Bay (Fig. 3.1) where the ice season is longest. The annual mean values of H_s are highest when using type F statistics and lowest when type I statistics are used; the differences in the annual mean values are up to 0.3 m. The annual mean values of H_s calculated with type N statistics are between the values given by type F and I statistics. As discussed in paper I, the wind forcing used in the wave hindcasts is calculated with an NWP system that takes the ice cover into account when calculating the surface flux of momentum. The model uses a higher surface roughness for ice than for open sea. Thus, the wind speeds are lower than they would be if the sea area was ice-free. Moreover, the stable boundary layer (the typical stratification over fast ice) also reduces the surface wind stress compared to neutral or unstable stratification. Due to this, the presented annual mean values of H_s calculated by type N statistics are estimated to be smaller than they would be if the sea remained ice-free throughout the year.

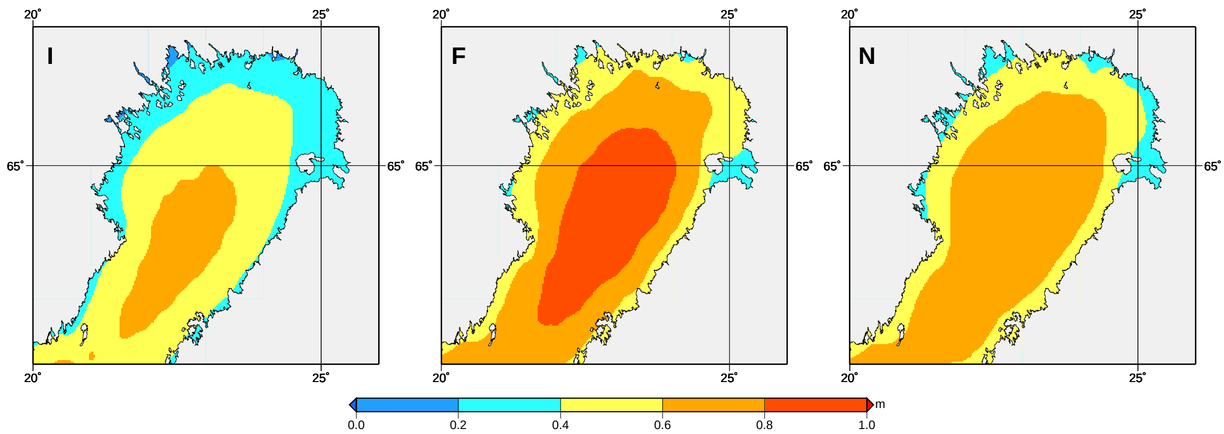

Figure 3.1: Hindcast annual mean values of significant wave height in the Bothnian Bay using ice-time-included (type I), ice-free time (type F) and hypothetical "no-ice" (type N) formulations of the statistics.

Each of the different types of statistics have an application for which they are the most appropriate, as discussed in paper I. To give a few examples, type F statistics give the highest mean values (Fig. 3.1); this it is a good choice when conservative estimates of the wave climate are needed. Also when the marine traffic operation limits according to the

SOLAS[1] treaty are defined, type F statistics is an appropriate choice. For the estimation of wave energy resources, type I statistics is a good choice, since it accounts for the time of the year when there is no wave energy available due to the ice cover. Type I statistics is also a good choice when fatigue loads for offshore structures are estimated, since the loads under ice conditions are generally taken into account separately. When statistics type I and F are presented as exceedance time (type ET) instead of exceedance probabilities they are equal, except for the time when significant wave height is zero. Therefore, the use of type ET statistics is recommended whenever it is applicable.

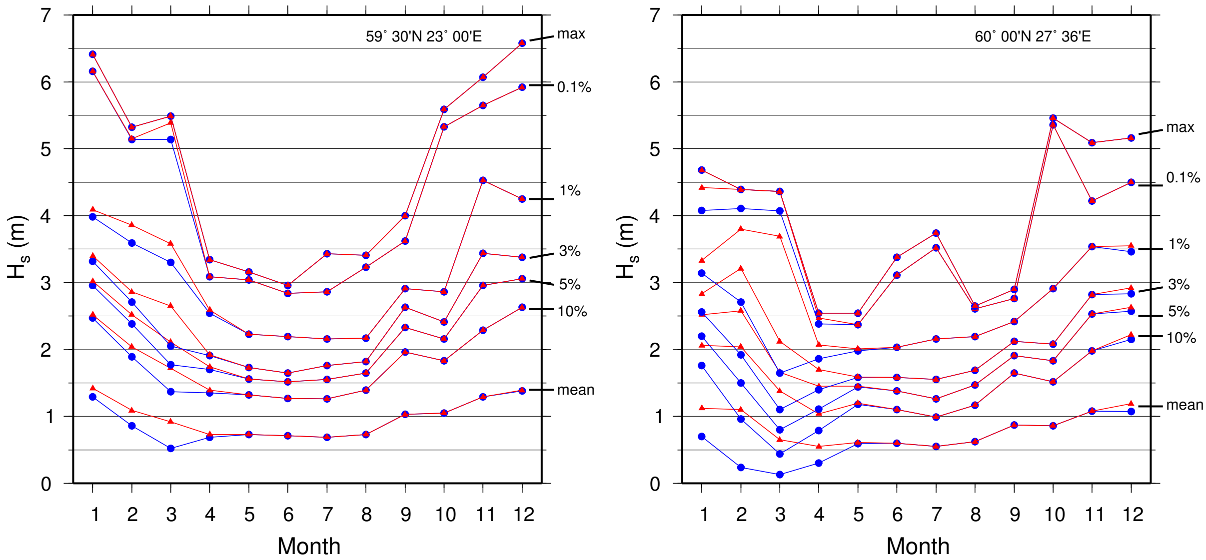

Figure 3.2: Monthly mean and maximum values together with exceedance probabilities of 10 %, 5 %, 3 %, 1 % and 0.1 % in the western (on the left) and eastern (on the right) GoF. Values calculated using type F statistics are shown with red triangles, and type I statistics with blue circles.

The different ways of formulating statistics cause significant differences in the mean values and exceedance probabilities also in the monthly stratified statistics during the ice season. In the GoF, the eastern extremity of the gulf has an ice cover even in the mildest winters, and the ice season there is typically longer than in the western part. The differences between the monthly mean values and exceedance probabilities during the ice season calculated with type F and I statistics are larger in the eastern part than in the western part of the gulf (Fig. 3.2). The differences are largest in February and March, decreasing towards the beginning and the end of the ice season. In the GoF the type F and I statistics give consistent results from May till November.

The question about how the statistics should be formulated in seasonally ice-covered seas is not limited only to surface waves. Similar problems in the formulation of statistics apply also for other surface parameters, such as surface temperature. Korhonen (2002), for example, discusses the effect that the missing temperature measurements at the beginning and end of the ice season in Finnish lakes have on the accuracy of the statistics.

[1]The international convention for the Safety of Life at Sea (SOLAS) is a maritime safety treaty which specifies minimum standards for the construction, equipment and operation of ships.

3.2 Open sea wave conditions

In the open sea areas of the Baltic Sea, wave conditions have been described based on measured data, e.g., by Kahma et al. (2003), Broman et al. (2006) and by modelled data by Jönsson et al. (2003), Räämet and Soomere (2010), Soomere and Räämet (2011) and paper I. The advantage of measured wave statistics is that it gives an accurate description of actual wave conditions at the measurement locations for the time period of the measurements. Due to the spatial and temporal limitations of the measured data, wave statistics based on wave hindcasts are also needed. In paper I the open sea wave conditions of the Baltic Sea were presented using annual mean values and exceedance probabilites (percentiles) using type I statistics. Verification of the hindcast significant wave heights in paper I showed that the accuracy in making representative statistics was good. In a comparison of the annual statistics, the hindcast significant wave height was shown to be a slight underestimate when compared to the buoy measurements. Annual mean values of significant wave height in the Baltic Sea were smaller than 1.5 m. The gulfs had a less severe wave climate than the Baltic Proper. The statistics presented in paper I are not directly comparable to those presented e.g. by Räämet and Soomere (2010) and Soomere and Räämet (2011), since these papers present no-ice statistics (type N), whereas in paper I ice-time-included statistics (type I) are presented. The period over which the statistics are calculated also differs. Nevertheless, the general features of the wave climate are similar in these papers: the Baltic Proper has the highest annual mean values, while the other sub-basins have a milder wave climate. Of the other sub-basins the Bothnian Sea has the highest annual mean values of H_s.

3.2.1 Maximum values of significant wave height in the northern Baltic Sea

The maximum values of hindcast significant wave height in the northern part of the Baltic Sea based on results, presented in paper I, are shown in Fig. 3.3 together with the maximum values of significant wave height measured by the FMI's operational wave buoys. In the northern Baltic Proper, the Gulf of Finland and the Bothnian Sea the measured and hindcast maximum values of significant wave height are of same order of magnitude. In the Bay of Bothnia the measured maximum value is considerably smaller than the hindcast maximum value. As discussed in paper I, due to the ice conditions, the wave buoys have to be recovered well before there is a risk of ice in the area. In the Bothnian Bay this means that there are typically measurements from June to November. Moreover, the period from which the measurements are not available partly coincides with the time of the year having the highest wind speeds. Also, the operational wave measurements in the Bay of Bothnia did not start until 2012, so the measurement period is short for evaluating the maximum values in this area. This is also the case at the Bothnian Sea wave buoy location, where the measurements started in 2011. In the northern Baltic Proper, the highest measured significant wave height of 8.2 m is smaller than the highest hindcast significant wave height of 9.7 m presented in paper I. The wave buoys are not necessarily located at sites of the highest hindcast significant wave heights. Additionally, the periods for which there is measured and hindcast data differ.

The Northern Baltic Proper wave buoy has measured a significant wave height of over 7 m four times during its measurement history (twice in December 1999, in December 2004 and in January 2005). Two of these events are within the period of the wave hindcasts presented in paper I. There is a relatively high variability in the northern Baltic Sea wave

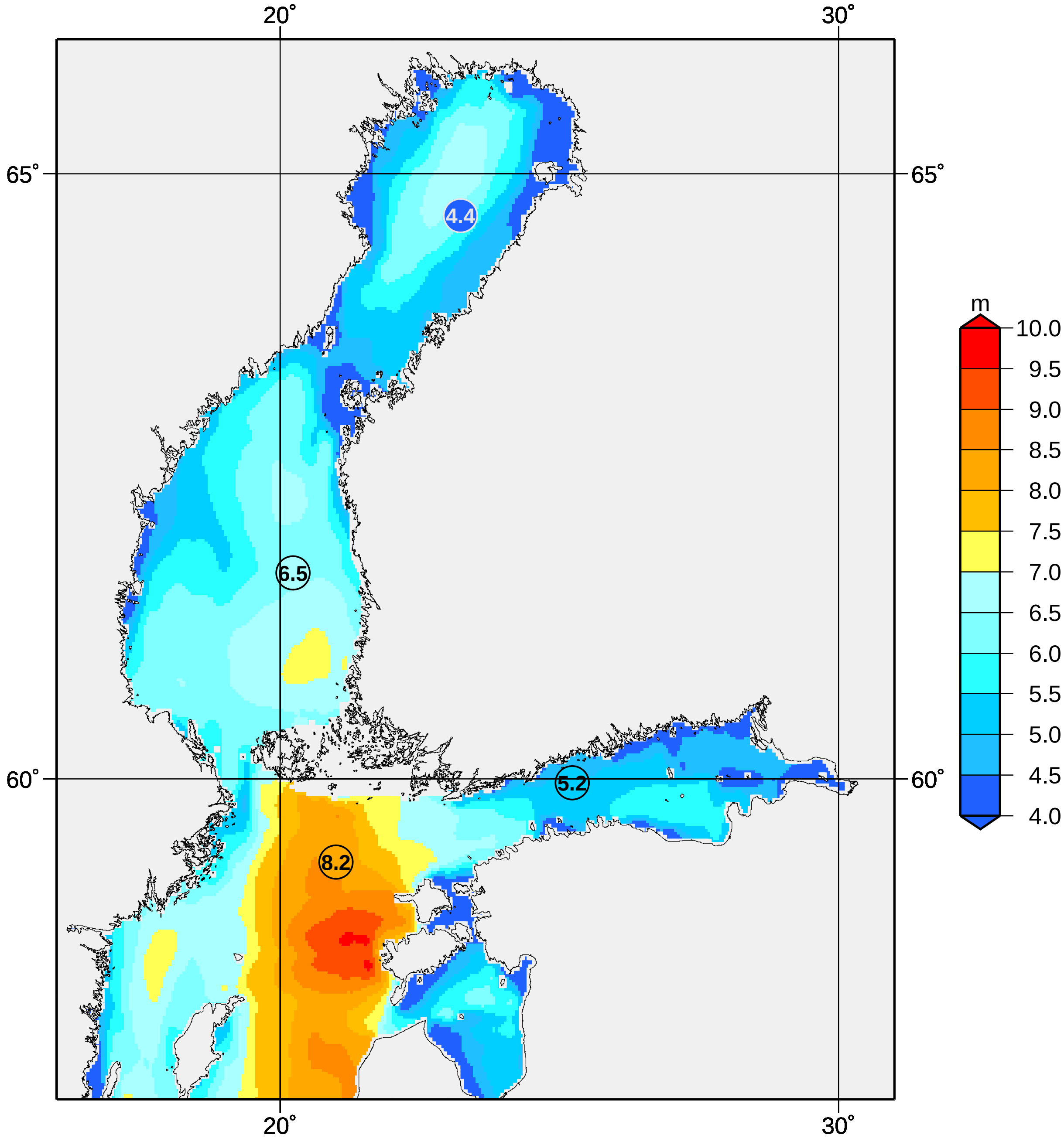

Figure 3.3: Hindcast maximum values of significant wave height in the northern Baltic Sea (redrawn from Fig. 14 in paper I, hindcast period Nov 2001 – Oct 2007) and highest significant wave heights measured by the FMI's operational wave buoys (locations shown in Fig 2.1). The circles mark the locations of the wave buoys, the colour inside the circle representing the value of the maximum measured significant wave height using the same colour scale as for the hindcast maximum values. The measured maximum values are also given inside the circle.

climate, when the highest significant wave heights are considered. Changes in the wind climate and in the extent of the seasonal ice cover (Fig.1.3) have a significant effect on the wave climate. In high wind situations the waves are typically fetch-limited due to the small size of the Baltic Sea, and a change in the direction of the high wind speeds will have a notable effect on the magnitude of the highest significant wave heights during the high wind situations. As discussed in paper I, the Northern Baltic Proper has the longest fetch from the south and south-west (cf. Fig. 1.2). High wind speeds from these directions will grow higher waves than winds from other directions, given similar wind speeds and event duration.

The temporal coverage of the hindcasts presented in paper I was six years. For the evaluation of maximum values of significant wave height this period is too short. For example Soomere and Räämet (2014) have shown that when longer time periods are considered, there are notable changes in the areas where the highest mean values of significant wave height occur in the Baltic Sea. Although, the location of the highest mean values is not necessarily exactly the same as the location of the maximum values of significant wave height, the decadal changes in the location of the highest mean values indicate that there are changes in the prevailing wind direction[2], which also indicates changes in the spatial distribution of the maximum values. However, as was discussed in paper I, the direction of the highest wind speeds in a basin may differ from the prevailing wind direction. In the Bothnian Sea, for example, the highest values of significant wave height were found in the south-eastern part of the basin (Fig. 3.3), indicating that during the period presented in paper I the highest wind speeds in this area were from the north-west, although the prevailing wind directions were south and south-west.

3.2.2 Seasonal variation in the wave conditions

The characteristics of the seasonal variation in the Baltic Sea wave climate have been shown in several studies based on measurements and model simulations (e.g. Pettersson, 2001, Jönsson et al., 2003, Räämet and Soomere, 2010, paper I). Based on the wave hindcasts presented in paper I, in the Northern Baltic Proper the highest values of significant wave height are reached during autumn and winter (Fig. 3.4). Summer has the mildest wave climate; the maximum value of H_s in summer, 3.59 m, is less than half of the maximum value of H_s in winter, 8.49 m. As shown in Fig. 3.4, the seasonal values of significant wave height exceeded for, e.g., 10% of the time are highest in winter (ca. 2.9 m) and smallest in summer (ca. 1.5 m). During summer there is also a higher percentage of H_s values smaller than 1 m than during any other season.

In sub-basins where the ice season is longest, such as the Bothnian Bay, the seasonal variation in the significant wave height slightly differs from that presented here for the northern Baltic Proper. There, the ice-covered periods partly coincide with the windiest time of the year, and the wave conditions during the winter season are significantly damped by the ice cover.

[2] Prevailing wind direction is defined as the direction with the highest frequency of occurrence within the given time period.

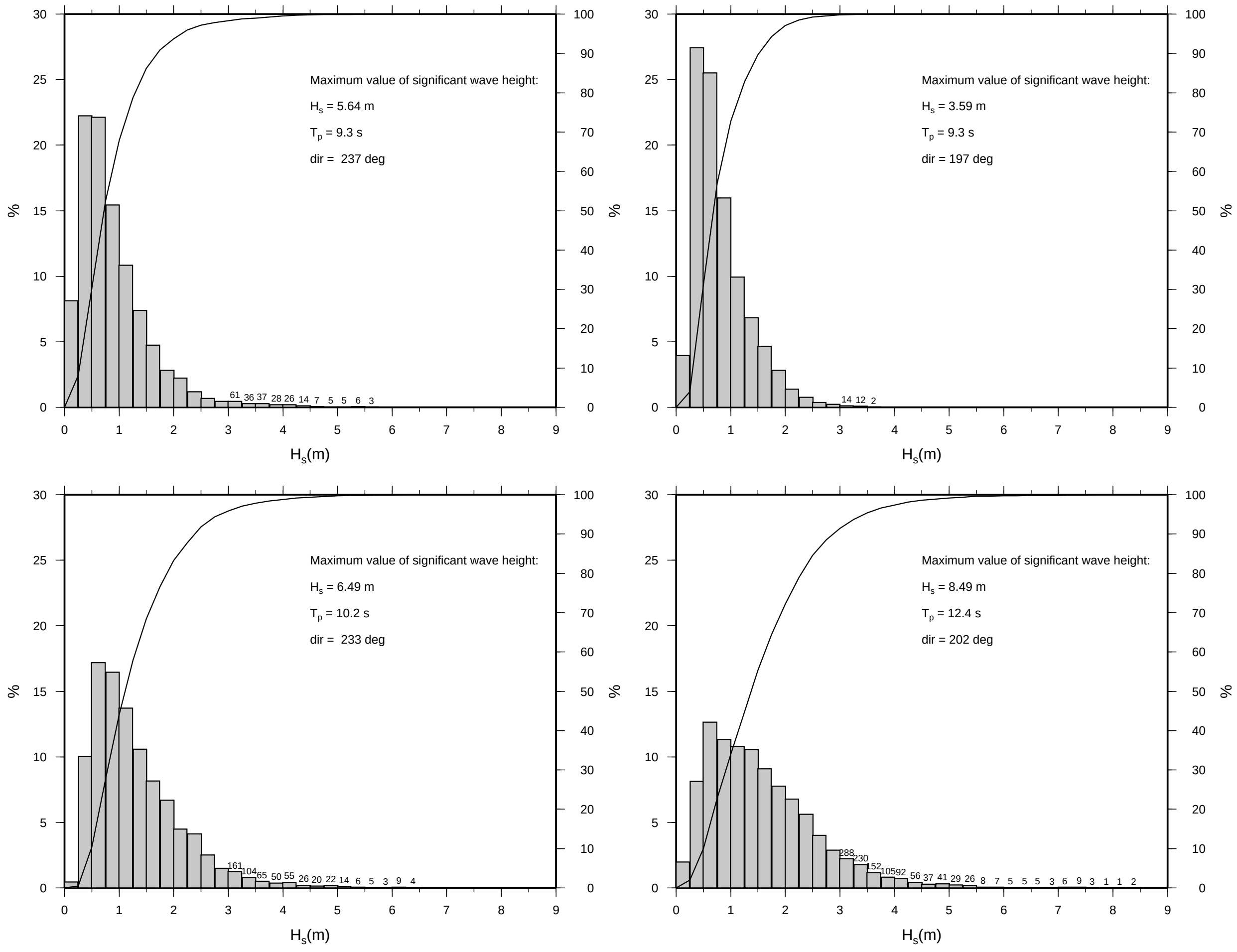

Figure 3.4: Distributions of hindcast significant wave height in the Northern Baltic Proper close to the location of the NBP wave buoy (cf. Fig.2.1) in spring (upper left), summer (upper right), autumn (lower left) and winter (lower right) calculated from the wave hindcasts presented in paper I for November 2001 – October 2007. The percentages of the total amount of data is given on the left y-axis and the percentages for the cumulative curve on the right y-axis. H_s classes are given at 0.25 m intervals and the number of hours for significant wave heights of over 3 m is shown above each bar. The maximum value of significant wave height for each season is given, together with corresponding peak period and its direction.

3.3 Wave conditions in coastal areas

Coastal wave conditions have been studied in the Baltic Sea e.g. by analysing visual wave observations made in the coastal areas of Estonia, Latvia and Lithuania and by performing model studies (e.g. Kelpšaitė et al., 2011, Zaitseva-Pärnaste et al., 2011, Suursaar, 2013, papers II and IV). These studies have shown that in coastal areas the wave climate is milder than in the open sea areas.

Modelling the coastal wave conditions with sufficient accuracy for the Finnish coasts requires the use of high-resolution grids. The basin-scale wave model applications for the Baltic Sea typically have resolutions between 2 nmi and 6 nmi (e.g. Soomere et al., 2008). These applications have been shown to accurately model the open sea conditions in the

Baltic Sea (e.g. paper I). However, for the modelling of the coastal areas these resolutions are too coarse. For example, accurate modelling of the effects of an irregular shoreline on fetch-limited wave growth requires the use of grids with resolutions smaller than 1 nmi (paper II). When modelling the sheltering effect due to archipelagos, and depth-induced wave breaking and wave refraction on shoals, even higher resolution is needed (paper IV).

3.3.1 Fetch-limited wave growth from an irregular shoreline

The irregular shorelines of the northern Baltic Sea affect the modelling of fetch-limited wave growth. As described in section 2.5, defining an optimal resolution and shoreline configuration for the model grid is a challenging task. In paper II different resolutions and shoreline descriptions were used to model the fetch-limited wave growth on the eastern coast of the Bothnian Sea. The use of different grids resulted in significant differences in the modelled growth of wave energy near the coastal areas. However, the differences were insignificant with longer fetches (more than 40 km). A high-resolution and detailed shoreline description in the model grid are therefore important when one's interest lies in the modelling of the coastal areas. In the case of fetch-limited wave growth, the coarser-resolution grids, such as those used in operational forecasting in the Baltic Sea, overestimate the significant wave height for short fetches, but give sufficiently accurate results for longer fetches.

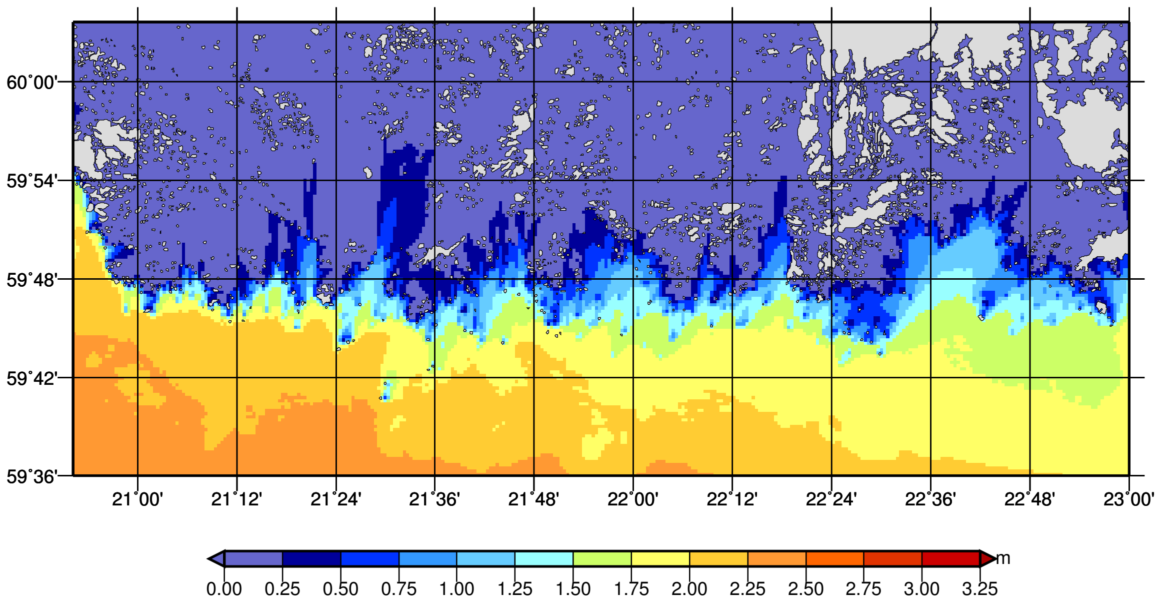

Figure 3.5: Attenuation of the significant wave height propagating from the Baltic Proper into the Archipelago Sea. A coarse-resolution model run with a constant wind speed of 12 m/s from south (run until steady state) was used as a boundary condition for the high-resolution grid. The high resolution model grid was run without wind forcing in order to describe the attenuation of the open sea wave field without the local growth of wind waves.

3.3.2 Sheltering

The Finnish coastal archipelago shelters the main shoreline from the open sea waves. Wave measurements made in the coastal area of the Bothnian Sea (Kahma, 1981a) and in the Archipelago Sea (paper IV) show that the wave energy is significantly attenuated when the waves enter the archipelago. If the growth of local wind waves is excluded from the wave model calculations, the attenuation of the open sea wave field entering the ArchS can be clearly seen (Fig. 3.5). Only in a few places are the islands so sparsely scattered that the open sea waves can enter further into the ArchS. Most of the open sea wave field is already attenuated at the southern edge of the archipelago. Inside the ArchS the wave field is thus mostly dominated by local wind waves. Such sheltering is also found in the coastal areas of the GoF (Fig. 3.6). When a high-resolution grid is used in the wave model, the attenuation of the wave energy in the outer archipelago is seen: in the coastal zone of the GoF, wave conditions are much less severe than in the open sea. Using coarse-resolution grids, one is not able to model this phenomenon unless the sheltering effects of the small islands are taken into account as grid obstructions (paper IV).

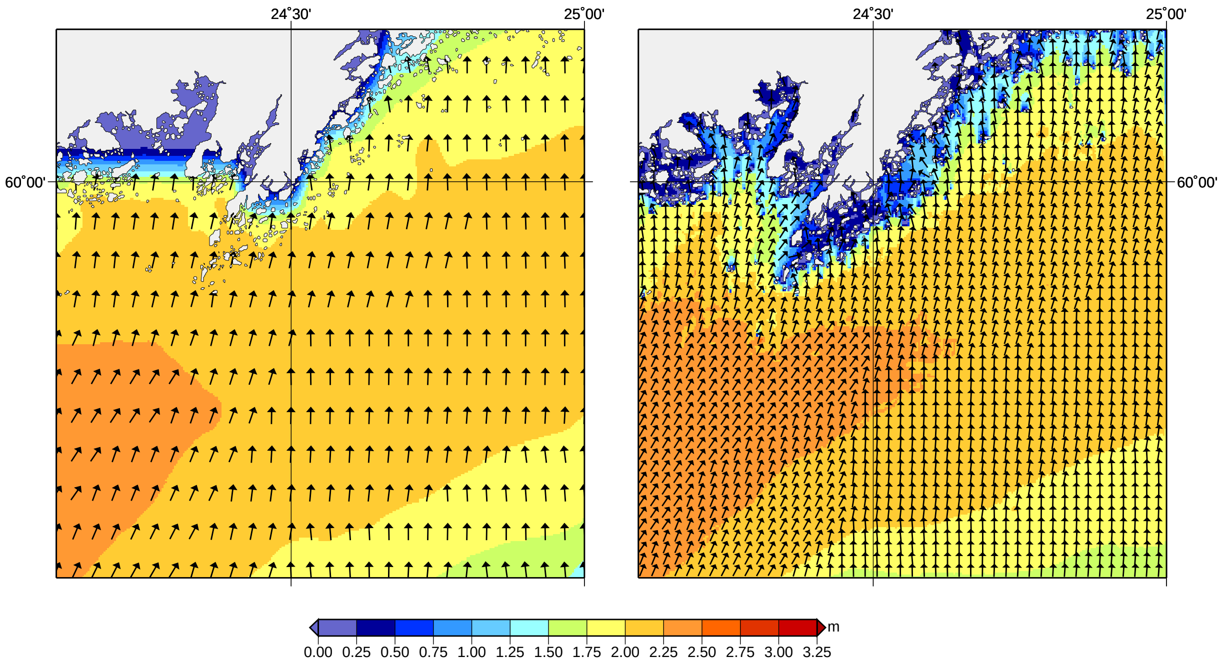

Figure 3.6: Modelled significant wave height and wave direction near Porkkala in the Gulf of Finland with a 2 nmi resolution grid based on ETOPO1 (on the left) and with a 0.1 nmi resolution grid based on coastal nautical charts (on the right).

3.3.3 Depth-induced wave breaking and refraction

Shoals are common in the coastal areas of Finland, and these may cause depth-induced wave breaking and wave refraction. Studying the effects which these phenomena have on the wave field requires a bathymetry with a high spatial resolution and accuracy. It was shown in paper IV that, if the resolution is not high enough to describe the variations in depth, the effects of both depth-induced wave breaking and wave refraction are considerably damped (Fig. 3.7). This may lead to an underestimation of the significant wave height near shoals where wave refraction, and thus the concentration of wave energy, is prominent. The appropriate description of these phenomena is important, e.g., when designing optimal locations for offshore structures or coastal fairways.

The modelling of depth-induced wave breaking and refraction is highly sensitive to the representativeness of the bathymetric data. On nautical charts there are areas where high-resolution bathymetric data is not available or even where there is a complete lack of data. Due to this, the bathymetries based on depth information available on the nautical charts may not be accurate enough when modelling these phenomena. It was shown by Hell et al. (2012) that, due to the deficiencies in the bathymetric data on nautical charts, freely-available bathymetries may have up to ca. 30% too shallow mean water depths compared to bathymetries based on depth information with a higher spatial resolution.

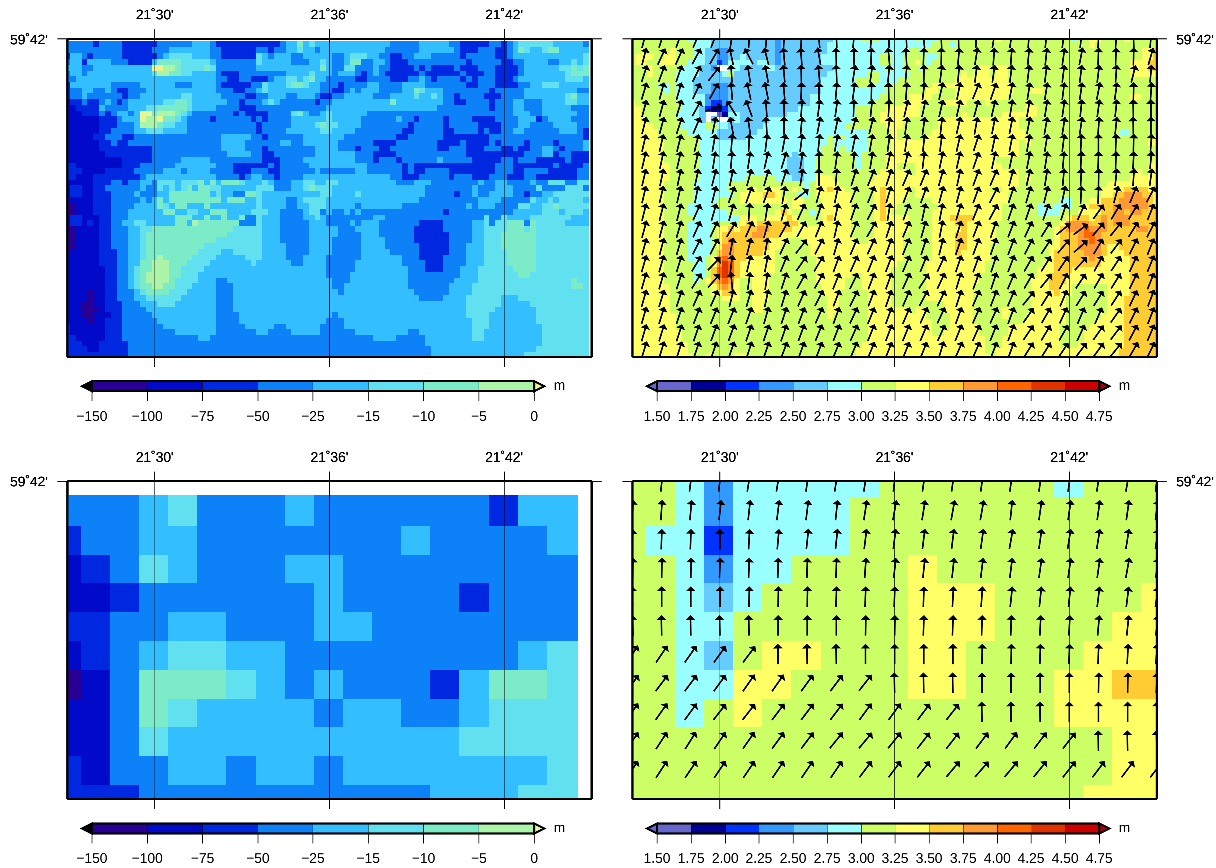

Figure 3.7: Bathymetry with a 0.1 nmi (upper left) and a 0.5 nmi resolution(lower left) in the northern Baltic Proper close to the Archipelago Sea and the significant wave height and wave direction calculated with WAM using a 0.1 nmi grid (upper right) and a 0.5 nmi grid (lower right) on September 16$^{\text{th}}$ 2010 at 12 UTC.

4 Factors affecting the accuracy of modelling in the Baltic Sea

The accuracy of the modelled parameters depends on several issues, and it is not always easy to distinguish a specific reason for the inaccuracies. The implementation of a model, the selection of an appropriate resolution, bathymetry and land-sea mask: all have a significant effect on the accuracy of the modelled parameters, especially near the coastal areas, as was shown in papers II and IV. The boundary conditions also affect the accuracy of the marine models significantly and therefore their specificity plays an important role. Furthermore, there is still a lot to discuss and study in order to understand the physics of the oceans thoroughly and find comprehensive equations to describe it. Moreover, some equations need to be parametrised, either because there is no explicit analytical solution to them or because the phenomenon happens on scales smaller than the resolution. Also different numerical solutions can be used, e.g., in the advection equations, that affect the accuracy of the modelled parameters.

4.1 Meteorological forcing datasets

The modelling of surface waves and 3D hydrodynamics in the Baltic Sea requires meteorological datasets with a sufficiently high accuracy and spatial resolution. As discussed in section 2.3, various different sources for the meteorological forcing are available. NWP systems provide data that can be used as input for marine modelling and forecasts. In the open sea areas the quality and the horizontal resolution (e.g. 4 nmi in FMI's present NWP system HIRLAM) of them have been found to be sufficient to make reliable wave forecasts (e.g. Tuomi, 2008).

In coastal areas a higher-resolution meteorological forcing is required. Nowadays, some limited area NWP systems are available having resolutions of a few kilometres. However, the domains of these models is quite limited due to their high computational cost. FMI is now running also NWP system HARMONIE for the northern Baltic Sea with ca. 2.5 km resolution. This gives us the possibility of carrying out marine modelling in e.g. GoF using wind fields that better describe the conditions in this narrow gulf.

To improve the physics and numerics of the wave and hydrodynamic models, modelling studies for past time periods that have representative measurement datasets are needed. The operational archives are not necessarily the best tool for this kind of studies. Due to the continuous upgrades in the resolution, physics and numerics of the operational systems, datasets compiled from this source tend to have a heterogeneous quality (e.g. Caires et al., 2004, Eerola, 2013, paper I). To obtain a meteorological dataset with homogeneous quality, re-analyses have been made using the present atmospheric models. However, in small basins the available re-analysed meteorological datasets are not necessarily more accurate or fit for the purpose than are the datasets compiled from operational archives. The resolutions of the re-analysed datasets are typically quite coarse in relation to the small size of the Baltic Sea. Of the existing re-analyses the ERA-40 (Uppala et al., 2005) and NCEP-NCAR (Kistler et al., 2001) have a horizontal resolution of more than 100 km. The downscaling of these re-analyses with limited area models has been shown to lead to increased accuracy. The downscaling of ERA-40 using SMHI's regional climate model RCA, with a horizontal resolution of 24.5 km (Höglund et al., 2009), has been shown to increase the accuracy of the meteorological parameters compared to the original ERA-40. However, Höglund et al. (2009) conclude that a further increase in the accuracy of this dataset, especially in the wind speed, would be necessary in order for it to be more suitable for modelling studies in the Baltic Sea.

In paper II the re-analysed wind field from FMI's NWP system HIRLAM was used for the year 1976. The surface wind field was modelled with sufficient accuracy to represent the growing wind speed from the shore to the open sea. However, the accuracy of a short-term weather forecast depends significantly on the data-assimilation made at the beginning of the forecast. The amount of measured data from earlier years is much smaller than at present. The accuracy of the re-analyses is thus not necessarily similar to that of the present NWP system. The dependence of the accuracy of the re-analyses on the availability of the measured data for data-assimilation has also been noted by Luhamaa et al. (2011) in the study of their 40 years of re-analyses made with the HIRLAM model.

Gridded meteorological datasets based on measured data, such as the dataset produced by SMHI for the Baltic Sea are also available. The quality of this dataset has been shown to be sufficient for modelling of the hydrodynamics of the Baltic Sea (e.g. Omstedt et al., 2005, Rudolph and Lehmann, 2006, Myrberg et al., 2010). However, it also has a coarse resolution, i.e., of 1 degree (ca. 110 km) only. In paper III it was shown that in the central part of GoF the daily mean values of air temperature were relatively well represented. However, the standard conversion of the geostrophic wind into a wind speed at 10 m height by Bumke and Hasse (1989) was shown to lead to underestimation of the wind speed in the Gulf of Finland. Hence, using more advanced methods when converting geostrophic winds to the surface winds might improve their quality and usability as forcing wind fields.

The challenge in evaluating the accuracy of the meteorological datasets in the open sea areas is that there are very few permanent weather stations in the Baltic Sea representative of the open sea condition, especially when all wind directions are considered. Sometimes the possible inaccuracies in the meteorological forcing can only be evaluated indirectly by verifying parameters that have been shown to have a strong dependence on only one meteorological parameter, such as the significant wave height on the wind speed or by using sensitivity analyses to study how a change in the meteorological forcing would affect the modelled parameters (paper III). The changes in the bias and the root mean square error of the significant wave height in open sea areas have been shown to be related to similar changes in the accuracy of the forcing wind field (e.g. Tuomi, 2008). The sensitivity of the model results to the changes in a certain forcing field can be studied by artificially changing the values of the forcing field (e.g. by increasing the values by a certain percent) and tracing the corresponding changes in the parameter or phenomenon in question. This kind of sensitivity study may tell us how important a role the forcing field might play in the modelling of the phenomenon.

In papers I, II and III it was discussed that the forcing wind speeds had a tendency to be underestimated in the open sea areas. The meteorological forcing used in these papers originated from different datasets: the forecast wind field from FMI's operational archive (paper I), the re-analysed wind field from FMI's NWP system HIRLAM (paper II) and the SMHI gridded dataset (paper III); the underestimation of the forcing wind speed in open sea areas thus seems to be of a general nature. Interestingly, it was shown in paper IV that increased resolution does not necessarily lead to increased accuracy in the forcing wind field. It was shown that the modelled wave field inside the ArchS was simulated with better accuracy when the HIRLAM wind field with a 4 nmi resolution was used than with the HARMONIE wind field having a resolution of ca. 2.5 km. It was shown that the use of HARMONIE, which overestimated the wind speed inside the archipelago, also led to an overestimation of the significant wave height. One reason behind this was suggested to be the land-sea mask used in the NWP systems in this area. The HIRLAM and HARMONIE NWP systems treat the different surface covers in the framework of a tiling approach, where each grid cell may contain several surface types, and each type is characterised by its own fractional coverage of the cell. At present the tools creating the land-sea mask for the atmospheric models use the ECOCLIMAP database (Masson et al., 2003) as a data source. In this database the shoreline information is based on 1 km resolution data. This resolution is too coarse to represent the archipelago areas in the northern Baltic Sea, as previously discussed.

Constructing a meteorological forcing dataset for the Baltic Sea marine models with sufficient resolution and accuracy is still an ongoing job. Recently Höglund et al. (2009) and Luhamaa et al. (2011) have presented re-analysed meteorological dataset for the Baltic Sea. Höglund et al. (2009) have shown that even though the wind speed in the dataset has a reasonably good accuracy, improvements are needed for it to better suit marine modelling. The accuracy of the dataset by Luhamaa et al. (2011) in representing the wind field over the Baltic Sea is still under study.

4.2 Horizontal resolution, land-sea mask and bathymetry

The representativeness of bathymetry and land-sea mask can have a significant effect on the accuracy of the model results. Andrejev et al. (2010) have shown that the effect of increased horizontal resolution and accuracy in the bathymetry on the simulated hydrodynamics of the GoF is significant. In paper II it was shown that an increase in the horizontal resolution increases the accuracy of the shoreline description in the Bothnian Sea, and thus leads to better model results during fetch-limited growth. Both by Andrejev et al. (2010) and in paper II the accuracy of the bathymetric data was increased by using information from nautical charts. In both studies the bathymetries and the shoreline descriptions were made manually. Such a method is laborious, and has to be done separately for each new grid with an increased resolution.

In paper IV automated methods for compiling model grids for the coastal archipelagos were presented. These methods enabled the use of threshold values for the land coverage at a grid point. Furthermore, a method for estimating the optimal location of land areas that overlap grid cell boundaries was presented (cf. section 2.5). With these methods a reasonable accuracy was obtained in areas where the shoreline structure was not very complicated. However, in complex archipelago areas the use of the additional grid obstructions was needed to achieve sufficient accuracy when using coarse-resolution grids (Fig. 4.1).

Furthermore, the choice of applicable resolution depends on the modelling task in question. For short-term simulations, the computational time demands are not so strict, and a high resolution may be used. In forecasting and in long-term simulations, the restrictions on the computational resources limit the resolution with which the simulations can be done. If the interest is in the modelling of the open sea areas, a detailed definition of the land-sea mask on the coastline is not as important, as was shown in paper II.

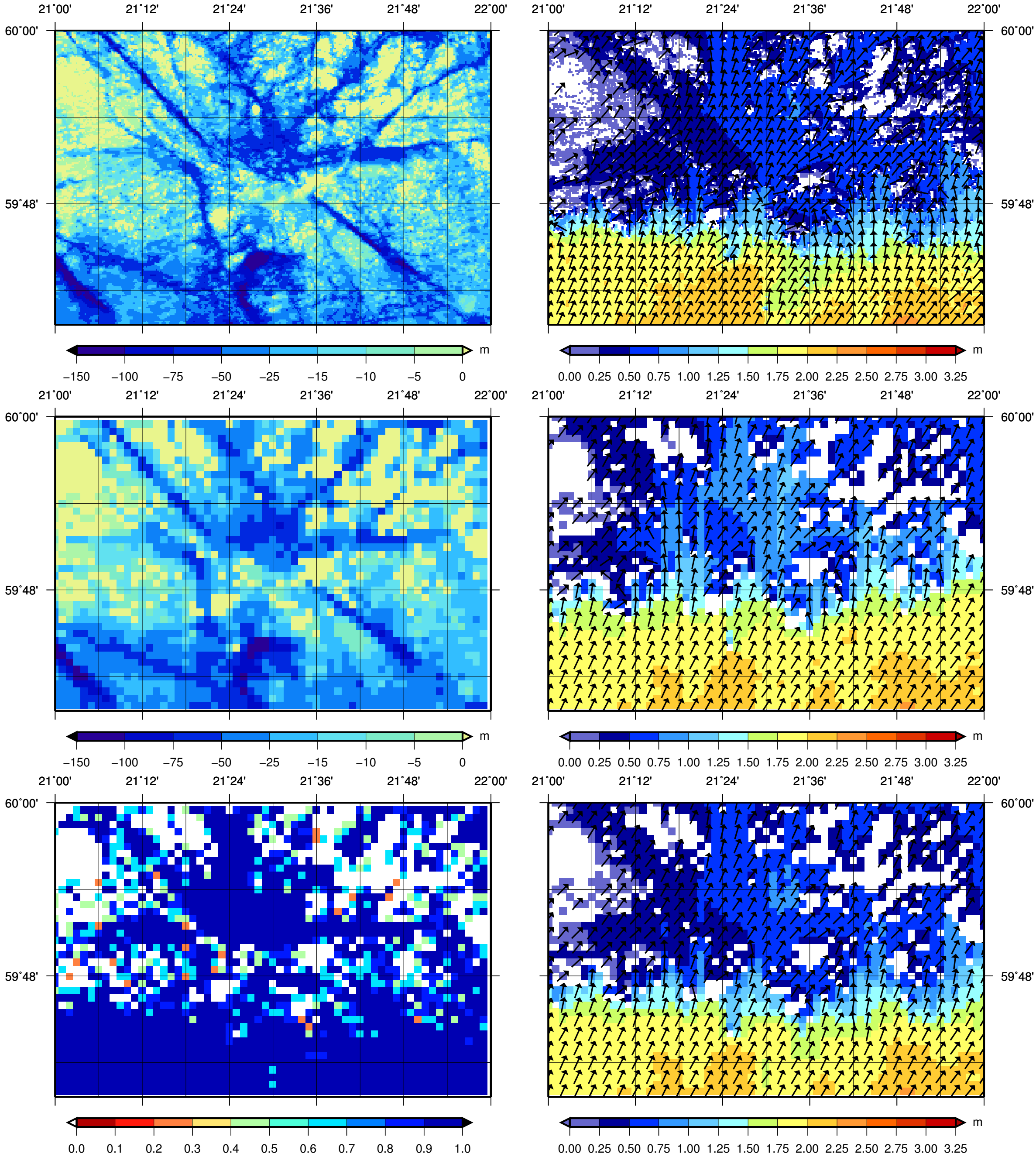

Figure 4.1: Bathymeries with a 0.1 nmi (on the upper left) and a 0.5 nmi (centre panel on the left) resolution. Modelled significant wave height and wave direction using the 0.1 nmi grid (on the upper right) and 0.5 nmi grid (centre panel on the right). Additional grid obstructions, given as the fraction of sea in a grid cell, used to reduce the wave energy transferred between the wave model grid points (on the lower left, obstructions given for north- and southward propagation directions) and significant wave height and wave direction using a 0.5 nmi resolution grid calculated using grid obstruction (on the lower right).

4.3 Initial conditions

When making short-term simulations with 3D hydrodynamic models, the accurate determination of the initial conditions for salinity and temperature is important, since they define the initial stratifications. This is not always an easy task due to the sparse observation network. For example in the GoF it is rare to obtain hydrographic measurements from the eastern extremity, and when compiling the initial fields extrapolation may lead to too high salinity values in that area. This overestimation diminishes once the model finds the balance between the fresh water from the voluminous runoff of the River Neva and the saline water penetrating from the western part of the GoF. However, this adjustment may need several months spin-up period (e.g. Andrejev et al., 2000, paper III).

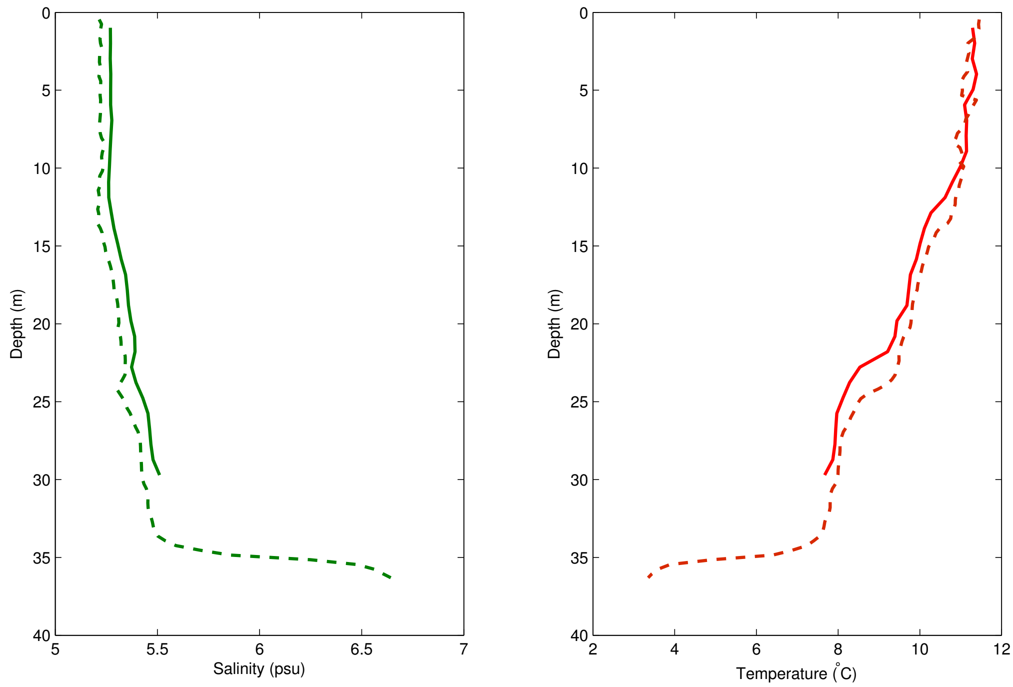

Figure 4.2: Salinity (on the left) and temperature (on the right) profiles measured in the GoF on June 5$^{\text{th}}$ 2013 at location 59°53.011′ N 24°16.308′ E. Measurements made with a Sea-Bird 911plus CTD instrument are shown with a solid line and measurements with a CastAway$^{\text{TM}}$ CTD instrument with a dashed line.

In short-term simulations the accuracy of the initial vertical structure of salinity also has a significant impact on the modelling. The initial values of salinity are mostly based on CTD[1] measurements. CTD instruments (e.g. Sea-bird 911plus) are used to make measurements of the vertical profiles of temperature and salinity. To avoid damaging the instrument in a possible bottom contact, the CTD is lowered to a depth of ca. 5 m above the sea-floor. In the GoF this means that, at some stations, the CTD measurements do not reach down to the bottom saline water. A preliminary analysis made with an additional measurement device (CastAway$^{\text{TM}}$), that can be lowered right down to the

[1]A CTD instrument measures the conductivity, temperature and pressure (depth) of the water.

sea-floor, showed that at certain locations there is a significant increase in salinity in the lowest 5 m above the seabed (Fig. 4.2). The availability of CTD data close to the seabed in the GoF has a significant effect on the accuracy of the initial vertical stratification of salinity in 3D hydrodynamic models. However, it is quite another question, whether the accuracy and resolution of the bathymetry of a 3D model are high enough to utilise the increased accuracy of the initial conditions, assuming that measured datasets would in future also include information on the bottom saline water.

4.4 Seasonal ice cover

As discussed earlier in section 2.6.3, it is important to take into account the seasonal ice conditions of the Baltic Sea when modelling the surface waves and 3D hydrodynamics. When ice concentrations are used as a boundary condition for a wave model, waves are not modelled in areas that have an ice cover. Furthermore, the fetch over which the waves grow is more precisely defined. Due to the changes in the fetch, the effect of ice cover on the wave field is not only felt in areas where there is ice cover but also in open sea areas surrounded by ice. However, when the change in the fetch is small, the effect on the significant wave height can only be seen close to the shoreline, as presented in paper II, or correspondingly close to the ice edge

In paper I the wave hindcasts were made both with and without ice concentration data to demonstrate the differences between the various ways of formulating wave statistics in the seasonally ice-covered seas, as discussed in section 3.1. In the Bothnian Bay, the distribution of H_s (Fig. 4.3) showed that the way ice conditions are handled when making the hindcast had a significant effect. The ice-included hindcasts have a significantly larger number of H_s values smaller than 0.25 m, since in the presence of ice the significant wave height equals zero by definition. The hindcasts excluding the ice information show a higher percentage of values between 0.25 m and 2.25 m than the ice-included hindcasts. However, there is no difference in the occurrence of the highest values of significant wave height (of over 4.5 m) between the ice-excluded and ice-included hindcast at this location.

4.5 Numerical solutions

The partial differential equations in the models are solved numerically by discretisation of the equations. There are different ways to do the discretisation of the equations in space and time (e.g. Press et al., 2007), and the selection of the methods in which these discretisations are made has an influence on the model results. Also, some processes happen at much smaller scales than the resolutions used in the models, and so have to be parametrised.

4.5.1 Nonlinear four-wave interactions

Even though the wave models have been shown to be able to describe the general features of the wave field in the Baltic Sea, they still have some deficiencies in describing the specific conditions related to e.g. fetch geometry. Pettersson et al. (2010) have shown that the directional properties of the wave field are not represented by WAM with sufficient accuracy in the narrow GoF. Although they showed that an increase in the horizontal

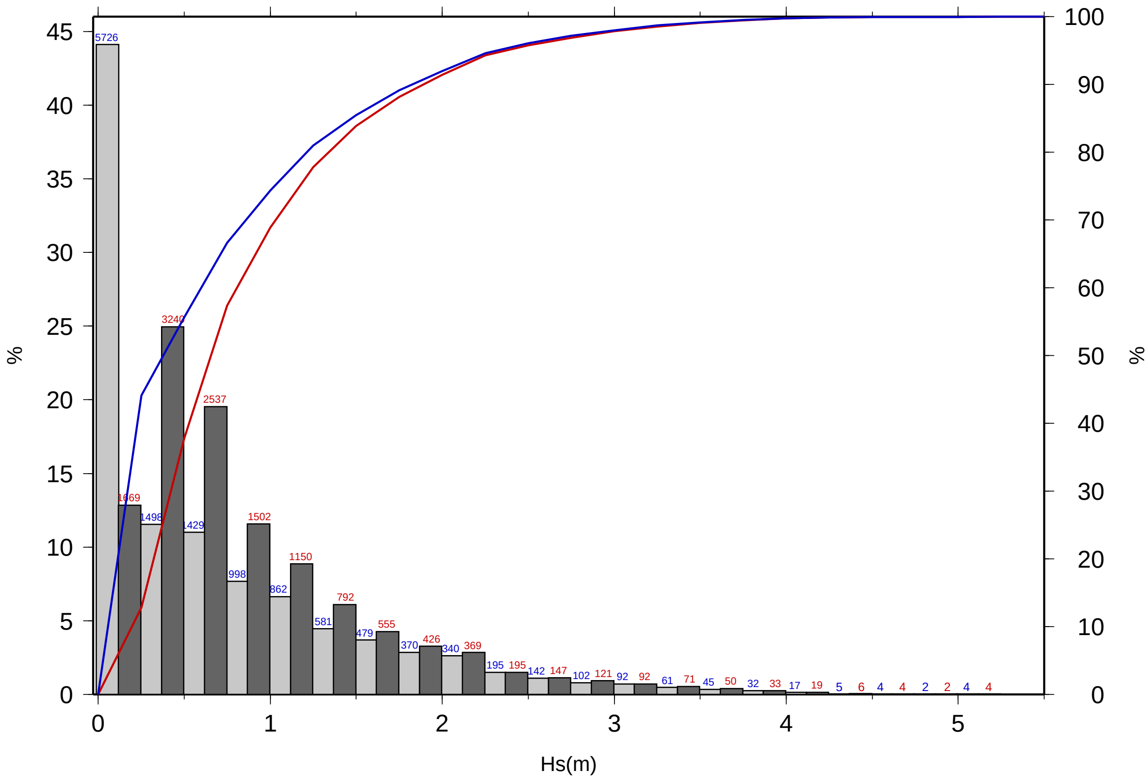

Figure 4.3: The distributions of significant wave height in the Bothnian Bay during winter (Dec 2001 – Feb 2007) based on six years of wave hindcasts, presented in paper I. The hindcast runs that utilised ice concentrations are shown in light grey and blue while the runs in which ice data were not used are denoted with dark grey and red. The bars represent the percentage of time (on the left y-axis). The number of hours a given H_s occurred within its 0.25 m interval is shown above each bar. The percentages for the cumulative curves are given on the right y-axis.

resolution improved the accuracy, there still remained a mismatch between the measured and modelled wave directions.

Pettersson et al. (2010) pointed out that one reason behind the inaccuracy in predicting the directional properties of the wave field in narrow gulfs could be the approximations used to calculate the nonlinear four-wave interactions. The WAM model uses the Discrete Interaction Approximation (DIA) method (Hasselmann et al., 1985) to calculate the nonlinear four-wave interactions. The DIA method is widely used, since it leads to sufficient accuracy in several areas and has a reasonable computational cost.

In paper II it was discussed that both the horizontal resolution and the description of the shoreline in the wave model grid affected the modelled growth of wave energy. It was also suggested that both the wave model physics and the numerics play a role in the inaccuracies in the modelling of fetch-limited wave growth. An additional study with the 1976 dataset was made using an alternative formulation for the nonlinear four-wave interaction source term S_{nl}, namely XNL (eXact calculation of the NonLinear four-wave interactions) by van Vledder (2006). The XNL formulation of the S_{nl} source term is based on the original formulation of the Boltzmann integral of Hasselmann (1962, 1963a,b), using additional considerations by Webb (1978), Tracy and Resio (1982) and Resio and Perrie

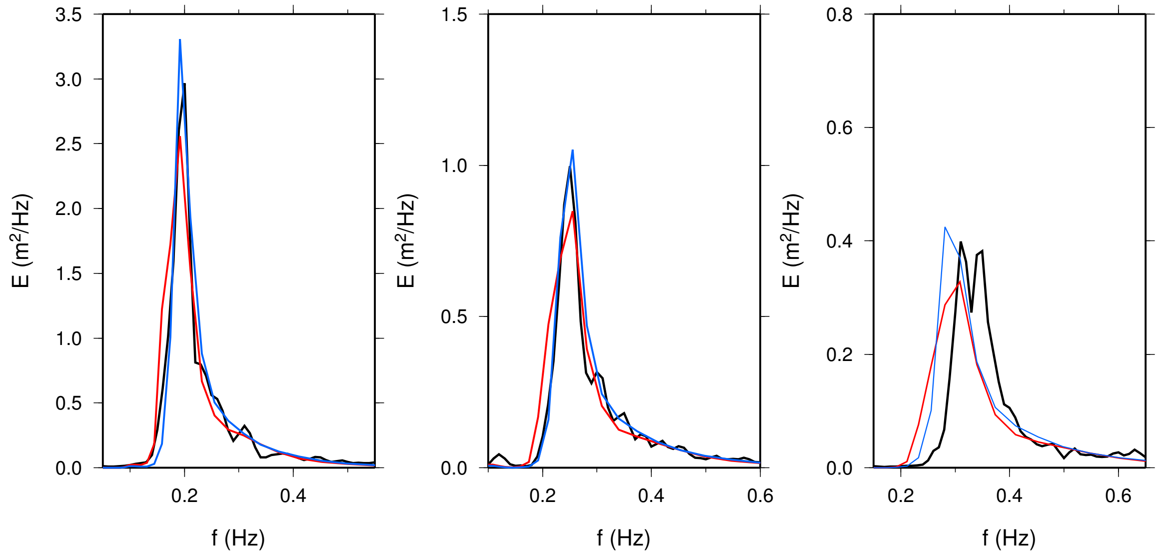

Figure 4.4: Measured spectra (black) from buoy B (on the left), from buoy C (in the centre) and from buoy D (on the right). Modelled spectra using the discrete interaction approximation (DIA) for the nonlinear four-wave interactions are shown in red and the exact calculation (XNL) of the nonlinear four-wave interactions in blue. Locations of the wave buoys are shown in Fig. 2.1.

(1991). It has been shown that the use of the exact solution for the nonlinear four-wave interactions leads to better modelling of the spectral shape (e.g. Cavaleri et al., 2007). However, the heavy computational cost of the calculation has restricted its use to scientific studies.

In the case of modelling the fetch-limited wave growth from the irregular shoreline, the use of the XNL improved the shape of the spectra compared to DIA (Fig. 4.4). However, the peak period and the significant wave height with XNL were quite similar to those modelled using DIA. The modelled growth of wave energy with a short fetch (less than 10 km) was not notably improved when XNL was used instead of DIA (not shown here). As discussed by Ardhuin et al. (2007) and Bottema and van Vledder (2008), an improvement in one of the source terms does not necessarily lead to an overall improvement in the wave model performance. The accuracy of the model is a complex combination of the balance between the source terms as well as the earlier-discussed model implementation and boundary forcing. A retuning of the balance between the source terms may therefore be needed before further improvement in the model performance is achieved. Even though, there was no significant improvement in the accuracy of the integrated parameters using XNL, the improved description of the spectral shape encourages its use in wave modelling in the Baltic Sea, whenever this is applicable.

4.5.2 Parametrisation of vertical turbulence

Turbulence in the oceans occurs at several different scales. It is not possible to solve all these scales in a model; typically, the large scales are solved and the smaller scales (i.e., smaller than the grid resolution) are parametrised. A good example of this is the parametrisation of vertical turbulence in the hydrodynamic models. Different types of turbulence parametrisations are available. The simplest approaches calculate the turbulent kinetic energy and the turbulent length scale through algebraic relations. An approach at one level higher is to calculate the turbulent kinetic energy from the transport equation and solve the length scale through an algebraic relation. The so-called two-equation models solve both turbulent kinetic energy and the turbulent length scale from differential transport equations. Several different solutions have also been presented for the so-called stability functions.

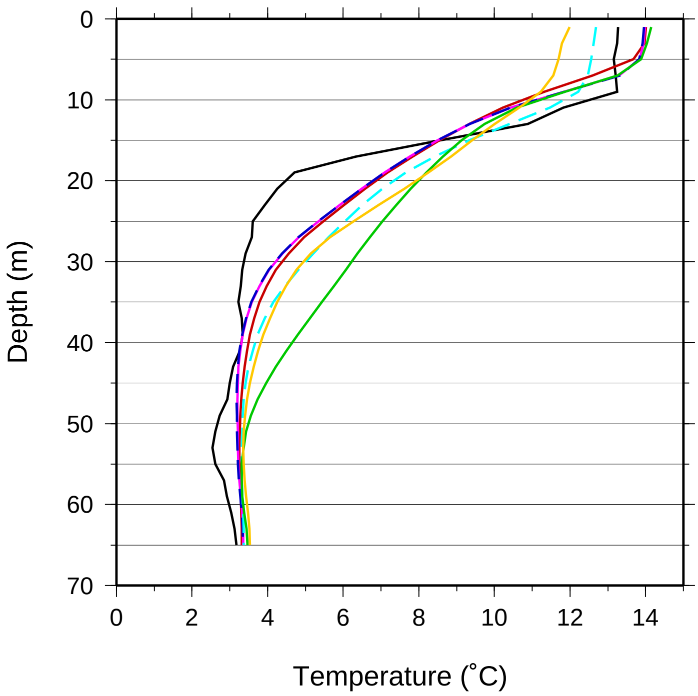

Figure 4.5: Measured temperature in the GoF (at 59°40.2′ N, 24°13.2′ E) on July 4th 1996 (black) compared against modelled temperature using COHERENS with different parametrisations of vertical turbulence. Shown are: the k-model with stability parameters by Luyten et al. (1999) with (red) and without (magenta) a limiting condition, and that of Munk and Anderson (1948) with (blue, dashed) and without (light blue, dashed) limiting conditions. Also show are the algebraic schemes by Pacanowski and Philander (1981) (green) and by Munk and Anderson (1948) (yellow).

In paper III the accuracy of different parametrisations of vertical turbulence in modelling the temperature and salinity in the Gulf of Finland was studied. The parametrisations included two algebraic relations and a k-model with different sets of stability functions (a more detailed description of the parametrisations used is given in paper III). When studying the accuracy of these parametrisations in modelling the vertical structure of temperature and salinity in the Gulf of Finland, the model implementation, boundary conditions and initial conditions were kept the same, so that the differences in the results could be linked to the differences in the parametrisation. The parametrisations used resulted in different solutions of the vertical and horizontal structure of temperature. Generally, the modelled profiles of temperature had a less steep gradient in the thermocline, and its depth was underestimated compared to the measurements (Fig. 4.5). No single parametrisation was found that performed best both in modelling the vertical and horizontal structure of temperature and salinity in the Gulf of Finland. The best accuracy in salinity was achieved with the algebraic parametrisation by Pacanowski and Philander (1981) while for temperature the vertical structure was best represented by the k-model using stability functions by Munk and Anderson (1948) with no limitation on the mixing length. However, as was discussed in paper III and e.g. by Meier (2001), the numerical stability of these two parametrisations may not be sufficient for long-term simulations.

In an intercomparison study of six different hydrodynamic models in the Baltic Sea it was shown, that the underestimation of the mixed layer depth was typical for all the models used in this study (Myrberg et al., 2010). New parametrisations of vertical turbulence have been presented in the past few years, and evaluation of the performance of these parametrisations in the modelling of the hydrodynamics of the Baltic Sea needs to be done. Especially considering the complex stratification conditions of the Baltic Sea, use of a parametrisation whose development has been specifically based on measurements made in the Baltic Sea (e.g. Lilover and Stips, 2011) should be considered.

As discussed in paper III, there are several possible reasons behind the underestimation of the thermocline depth. The sensitivity study made in paper III, in which the forcing wind speeds were increased to better match the observed values, was shown to slightly improve the accuracy of the modelled thermocline depth. However, it could not alone explain the underestimation of the modelled mixed layer depth. It was also discussed that the lack of an explicit description of the surface-wave-induced processes in the vertical mixing parametrisations might have an impact on the results.

5 Including surface wave processes in the modelling of marine systems

Current operational models simulating marine physics are able to mimic the properties of the Baltic Sea wave field, temperature, and surface currents with sufficient accuracy in the open sea areas. However, there are limitations in the process descriptions, e.g., at the atmosphere-ocean boundary, which can only be thoroughly resolved by using coupled models. The first fully-coupled atmosphere-wave-ocean models aimed for operational predictions, such as ECAWOM (e.g. Weisse and Alvarez, 1997) or COAMPS (e.g. Hodur, 1997), were developed in the 1990's. Even the first simple process descriptions of the coupled atmosphere-wave models led to increased accuracy in the modelled parameters (e.g. Järvenoja and Tuomi, 2002). Progress in the development of coupled atmosphere-wave-ocean models has led to more detailed process descriptions and an increase in the accuracy of the modelled parameters.

The complexity of the marine ecosystem makes its modelling a challenging task. It requires a thorough understanding and appropriate process descriptions in the modelling of both marine hydrodynamics and biogeochemistry. For instance, the intensity of primary production is largely determined by the nutrients available in the euphotic zone[1]. Density stratification restricts the transfer of nutrients between the bottom and the surface layer. In order to simulate the transfer of nutrients with sufficient accuracy, the vertical mixing processes and the vertical structure of temperature and salinity need to be simulated well by the hydrodynamic model. As discussed earlier, including the effect of surface waves might improve the description of the mixed layer dynamics in the models.

5.1 Modelling vertical mixing in the ocean surface layer

The importance of the surface waves as a part of the upper ocean mixing processes has been acknowledged for quite a long time (e.g. Phillips, 1977). However, the explicit description of the surface waves and their effect on mixing are still missing from most of the 3D hydrodynamic models. The specific stratification conditions of the Baltic Sea make the modelling of the vertical mixing a complicated task. It has been shown e.g. by Myrberg et al. (2010) and in paper III that the present hydrodynamic model and parametrisations of vertical turbulence are unable to describe the vertical mixing in full detail in the Gulf of Finland.

Belcher et al. (2012), for example, have shown that Langmuir circulation has a large effect on the ocean surface-layer mixing. They also showed, based on wave and surface stress measurements, that in the Baltic Sea, too, Langmuir circulation might play a significant role in the mixing of the surface layer. To evaluate the importance of Langmuir circulation in the turbulence production in the GoF, the wave spectra from the wave hindcast runs used to calculate the wave statistics in paper I were used to calculate the surface Stokes drift. As in Belcher et al. (2012), the component of the Stokes drift, u_s, aligned with the wind direction ϕ_w was calculated according to equation

$$u_s = \frac{16\pi^3}{g} \int_0^{2\pi} \int_0^{\infty} f^3 F(f,\theta) cos(\theta - \phi_w) df d\theta \tag{5.1}$$

[1]The sea surface layer that receives sufficient sunlight for photosynthesis to occur.

where $F(f, \theta)$ is the energy spectrum of surface waves (cf. section 2.1), f is the frequency and θ the propagation direction of the waves, and g is the acceleration due to gravity.

The Stokes drift together with the friction velocity u_* calculated by WAM, based on the surface wind at a height of 10 m supplied by the FMI's NWP system HIRLAM, were used to calculate the turbulent Langmuir number

$$La_{tb} = \sqrt{\frac{u_*}{u_s}} \tag{5.2}$$

which describes the relative influence of wind shear and the Stokes drift on the production of turbulence. The values were calculated with a 1 hour resolution for all cases in which the modelled wind speed at the height of 10 m exceeded 3 ms^{-1}. This wind speed limit was chosen based on Leibovich (1983) according to whom, Langmuir circulation typically forms when the wind speed exceeds a value of 3 ms^{-1}.

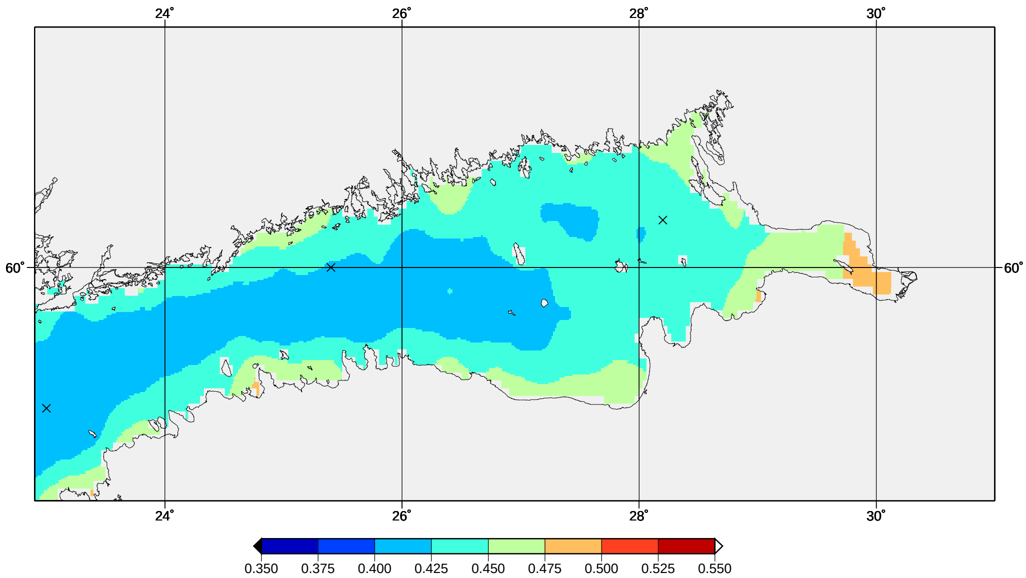

Figure 5.1: Hindcast mean values of the turbulent Langmuir number (La_{tb}) in the Gulf of Finland in summer (2002–2007) when the forcing wind speed exceeded 3 ms^{-1}. The locations for which the distributions of La_{tb} are shown in Fig. 5.2 are marked with an x.

The hindcast mean values of La_{tb} were smaller than 0.5 (Fig. 5.1) in the GoF in summer. La_{tb} had its lowest values in the central part of the GoF with the values increasing towards the shores. The distributions of La_{tb} from the eastern, middle and western GoF (Fig. 5.2) showed that La_{tb} peaked at around 0.4. In the western part of the gulf the peak value of La_{tb} is lower than in the eastern part, where the peak value of La_{tb} is over 0.4. Compared to the results presented in Belcher et al. (2012), the distributions of La_{tb} in the GoF have higher peak values, with the results representing those of coastal seas with under-developed waves.

Even though, the values of La_{tb} presented here are higher than those presented e.g. by Belcher et al. (2012), the Langmuir circulation may still play a significant role in the mixing of the surface layer. Li et al. (2005) suggest, based on Large Eddy Simulations

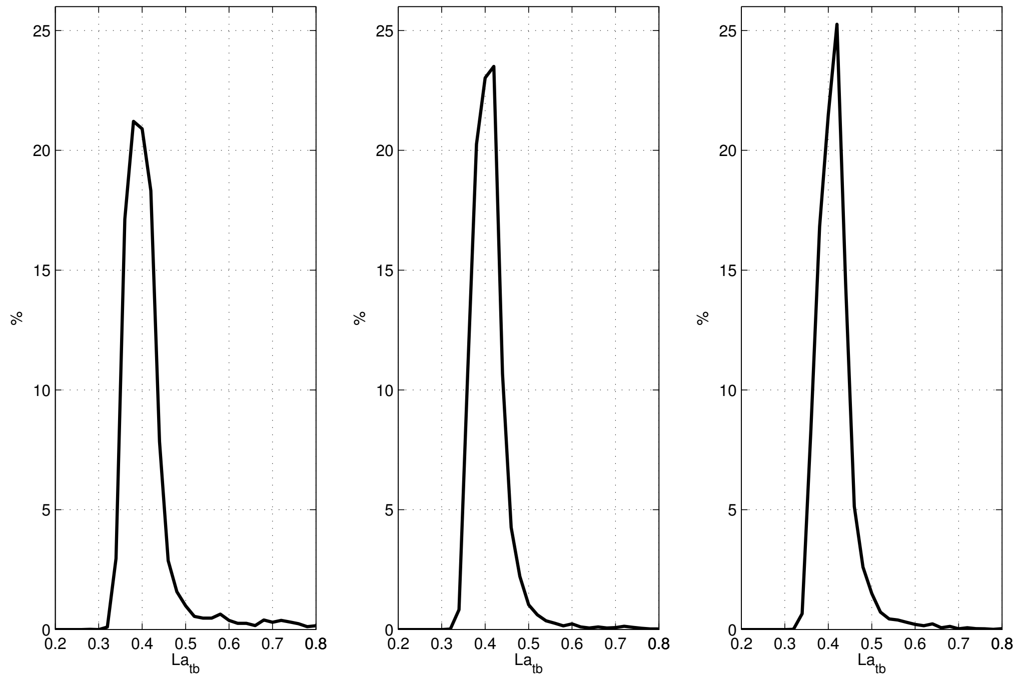

Figure 5.2: Distribution of hindcast values of La_{tb} given as a percentage of the time in summer in the western GoF (on the left), in the central GoF (centre) and in the eastern GoF (on the right) when forcing wind speed exceeded 3 ms^{-1}. The locations are shown in Fig. 5.1.

(LES), three regimes for turbulence: convective, shear and Langmuir. They found that the Langmuir circulation plays an important role in vertical mixing when $La_{tb} < 0.7$. However, the effect of Langmuir circulation on the production of turbulence is highest when $La_{tb} < 0.4$. At larger values, the role of Langmuir circulation diminishes rapidly. Grant and Belcher (2009) also obtained similar results based on LES. They suggest that Langmuir turbulence dominates when $La_{tb} < 0.5$ and that the transition between Langmuir and shear turbulence happens when $0.5 < La_{tb} < 2$.

When the hindcast wind speed was over 3 m/s, the values of La_{tb} in the GoF were mostly smaller than 0.6 (Fig. 5.2). Based on the threshold values presented by Li et al. (2005) and Grant and Belcher (2009), this suggests that Langmuir circulation might have an important role in the turbulence production in the GoF and that its inclusion into the modelling of vertical mixing should be considered in order to improve the simulations of the vertical structure of temperature and thus the thermocline depth.

5.2 Surface drift modelling

Making a drift forecast requires modelling of the marine physics as an entire system. The surface drift is a complex combination of the effects of the wind, currents and surface waves; in the seasonally ice-covered seas the ice also plays a part. The shape and composition (centre of mass) as well as the over- and underwater structure of the drifting object affects the drift. When the over-water structure of the object is large, it is more likely to be driven by the wind. Conversely, if the object has a large underwater structure, currents and wave-induced Stokes drift have more of an influence on the drifting of the object.

Röhrs et al. (2012), for example, have shown that if the drifting object is surface-following (resembling e.g. the behaviour of oil), the Stokes drift can have a high impact on the drift trajectory of the object. They also discussed the predictability of drift trajectories: this improves if wave information is added to the calculations. Rixen et al. (2008) have also shown that taking into account the combined effect of wind, currents and waves leads to more accurate predictions of the surface drift.

In areas such as the GoF, where the geometry steers the wave direction, taking into account the combined effects of wind, waves and currents on the drift is essential. There could be a difference of up to 50 degrees between the wind and wave directions (Pettersson, 2004), thus the direction of the surface drift induced by waves and wind may also differ. Comparison of drift calculations against surface drift measurements made on board R/V Aranda in GoF has shown that in some cases the taking into account of wave conditions improves the modelled drift of objects (e.g. Gästgifvars et al., 2004).

5.3 Modelling wave–ice interaction

In the seasonally ice-covered seas, the inclusion of ice conditions in the modelling of the surface waves and 3D hydrodynamics is important. In the present operational Baltic Sea 3D hydrodynamic models, such as HBM (Berg and Poulsen, 2012) (in operational use at FMI), an ice model with the thermodynamic and dynamic properties of ice is typically included. However, in wave models the ice conditions are often still given only as a boundary condition. In paper I, for example, the ice conditions were updated once a day based on the gridded ice data provided by the local Ice Service. This approach is similar to that used in the operational wave forecast model at FMI. In operational forecasts the ice concentrations are typically kept the same for the length of the forecast. When there are rapid changes in the ice field, in the case of a high wind situation for example, a more frequent update of the ice field could be beneficial for the accuracy of the forecast. Coupling an ice model with a wave model could be one option to improve the accuracy of the wave forecasts. By including in the ice models the effects that surface waves have on the ice field, e.g. by causing fragmentation, the accuracy of the modelling of ice conditions in the marginal ice zone may also be improved.

6 Summary and conclusions

In this thesis the northern Baltic Sea wave climate is presented based on six years of wave hindcasts. The hindcasts were produced taking into account the seasonal ice conditions and other specific features of the northern Baltic Sea. Five different ways of formulating wave statistics in seasonally ice-covered seas were discussed and the differences in the resulting wave climate and the different applications for the types of statistics were presented. The effect of the irregular shoreline in the coastal areas of Finland on the modelling of fetch-limited wave growth and the attenuation of waves when propagating into the archipelago were studied. The effects of the other specific characteristics of the Baltic Sea, such as its small size, shape, rugged sea floor, and its particular stratification conditions on the modelling of the surface waves and vertical mixing were also studied. The effects of the different numerical solutions used in the models on the accuracy of the model results were discussed, and the role of the surface waves in the mixing processes of the ocean surface layer was studied by evaluating the role of Langmuir circulation in the turbulence production in the Gulf of Finland based on wave hindcasts. The conclusions can be summarised in the following points:

1. There are several different ways of formulating wave statistics in the seasonally ice-covered seas. These formulations differ in the way in which the ice season is handled when making the wave hindcasts and when formulating the statistics. If the ice conditions have been taken into account in the wave hindcasts, the statistics can be formulated by including the time for which there is ice cover and defining that, in the presence of ice, the significant wave height is zero (ice-time-included statistics, type I) or by using only the time of the year, when the sea is ice-free (ice-free time statistics, type F). The statistics can be presented as exceedance times instead of percentages (type ET) when applicable. If the ice conditions are not included in the wave model calculations, the wave statistics may be presented as hypothetical no-ice statistics (type N). The way the statistics are calculated affects the mean values and the exceedance probabilities of the significant wave height. For example, in the Bothnian Bay, the largest differences in the mean value of significant wave height between type F and I statistics was of the order of 0.3 m, when the highest mean value in this area was smaller than 1 m. Each statistics type has a practical application for which the given type is more appropriate in describing the conditions than the others.

2. Due to the relatively small size of the Baltic Sea, the wave climate is less severe than e.g. that of the North Atlantic. The Baltic Proper, having the longest fetch of the sub-basins, has experienced the highest measured significant wave height, 8.2 m. The highest hindcast significant wave height in the Baltic Proper, 9.7 m based on six years of wave hindcasts, is located south of the location of the measured maximum. Of the other sub-basins, the Bothnian Sea has the highest maximum values. There the hindcast maximum value of significant wave height is over 7 m. The Gulf of Finland and the Bothnian Bay have a less severe wave climate. Due to the seasonal variation in the wind speed and direction, the highest values of significant wave height are reached during autumn and winter. Spring and summer have a considerably less severe wave climate. However, the seasonal ice cover affects the wave climate, and in the Gulf of Bothnia, the Gulf of Finland and the Gulf of

Riga the wave climate is less severe during the winter than it would be if the sea area remained open throughout the year.

3. The wave conditions in the coastal areas of Finland are considerably less severe than in the open sea. The irregular structure of the shoreline together with presence of the archipelago shelter the coast from the high waves of the open sea areas. In the Archipelago Sea the wave energy was shown to be considerably reduced when the wave field propagated from the open sea into the archipelago. Inside the archipelago the wave field was mainly dominated by the local wind waves. However, if there are shoals present at the edge of the coastal archipelago, the wave refraction caused by them may concentrate the wave energy: in the vicinity of a shoal the significant wave height may be considerably higher than in the surrounding areas. This phenomenon is important to take into account when planning offshore structures and fairways in the northern Baltic Sea.

4. Due to the small size of the Baltic Sea, high-resolution meteorological forcing is evidently needed to model the surface waves and 3D hydrodynamics with reasonable accuracy. It was shown, however, that an increase in the resolution does not necessarily lead to an increase in the accuracy of the modelled surface wind field in coastal archipelago areas. Special emphasis should be placed on further development of the numerical weather prediction systems so as to better describe the properties of the wind field in the coastal archipelagos. Since the further improvement of marine models requires re-analyses of past time periods, there is an immediate need for high-resolution re-analysed meteorological datasets with a high accuracy. Additionally for future projections of e.g. the ecological state of the Baltic Sea, climate scenarios with resolutions high enough to resolve the small basins of the Baltic Sea are also needed.

5. In the northern Baltic Sea, implementation of a marine model demands great accuracy in order to get reliable model results. The appropriate choice of bathymetry, resolution and land-sea mask is imperative in areas having rugged sea floor and irregular shoreline in order to adequately simulating both open sea and coastal conditions. Since it is not always feasible to use high resolution, especially when operational forecasting is considered, methods of generating representative grids for coarse resolution applications are needed. The manual and automated methods presented in this thesis have been shown to improve the representation of the land-sea mask used in the model grid and thus improve the model results in coastal areas. These methods are also applicable for different types of shorelines and archipelagos. The use of grid obstructions in the wave model opens up the possibility of reducing the amount of energy propagated between the grid points according to the coverage of the unresolved islands. The use of this method was shown to further improve the wave model results in archipelago areas and to allow modelling of waves with sufficient accuracy when a compromise in the grid resolution has to be made. However, additional methods are needed to take into account wave refraction and depth-induced wave breaking on sub-grid scales.

6. There are several possibilities open for the numerical and physical solutions used in models. With our current knowledge of the marine system and its processes, and with current computational resources, we are not able to model the marine physics

in full detail. The compromises we have to make in the resolution, numerics and physics in order to be able to run the models within the time restrictions of e.g. operational forecasting affect the skill of the models in many ways. It is not always easy to distinguish a specific reason for the inaccuracies of the model. Studies with different resolutions and meteorological forcing datasets, or the testing of different numerical solutions lead to a better understanding of what needs to be improved in the models. As an example, when modelling the fetch-limited wave growth from the irregular shoreline of the Bothnian Sea it was shown that none of the various combinations of horizontal resolution, land-sea mask and wind forcing used resulted in the observed fetch-limited growth of waves. However, it was clear that an increase in resolution did improve the behaviour of the model at short fetch. Additionally, a test of an exact numerical solution to the non-linear four-wave interaction source term was shown to improve the shape of the modelled spectra compared to the calculations made with the discrete interaction approximation of this source term. Even so, the overestimation of the significant wave height and peak wave period at short fetch was not notably reduced when the exact solution was used.

7. When the different parametrisations of vertical turbulence in modelling the vertical structure of temperature in the Gulf of Finland were studied, it was shown that none of the parametrisations used resulted in a sufficiently accurate solution. The thermocline depth was underestimated by all the parametrisations, and generally the modelled temperature gradient in the thermocline was less steep than in the measured profiles. The ability of a 3D hydrodynamic model to simulate the vertical structure of temperature depends on several factors and further studies are needed in order to produce more accurate simulations for the Gulf of Finland. One factor, the explicit representation of which is completely missing from most of the hydrodynamic models, is that of surface-wave-induced mixing. The turbulent Langmuir numbers found for the Gulf of Finland based on wave hindcasts indicate that the Langmuir circulation may play an important role in production of turbulence in this area. Thus, taking these effects into account when modelling the vertical mixing in the surface layer might improve the model behaviour.

8. The complexity of the marine system of the Baltic Sea requires its modelling as an entire system. Taking into account the surface-wave-induced processes in the ocean surface layer might lead to a better estimate of the vertical structure of temperature and thus improve the performance of e.g. the biogeochemical models in the Baltic Sea. Also, when modelling the surface drift trajectories of drifting objects, the taking into account of the combined effects of wind, waves and currents has been shown to improve the forecasts. The development of a coupled wave-ice-3D-hydrodynamic model, that can also function as a platform for biogeochemical models and drift prediction systems in the Baltic Sea, is therefore recommended.

List of abbreviations

ArchS Archipelago Sea

BP Baltic Proper

BSAP Baltic Sea Action Plan

BSH Bundesamt für Seeschifffahrt und Hydrographie (Germany)

COAMPS Coupled Ocean/Atmosphere Mesoscale Prediction System

COHERENS COupled Hydrodynamical Ecological model for REgioNal Shelf seas

CTD Instrument measuring water Conductivity Temperature and pressure (Depth)

DIA Discrete Interaction Approximation of the non-linear four-wave interactions

ECAWOM European Coupled Atmosphere Wave Ocean Model

ECMWF European Centre for Medium-Range Weather Forecasts

ERA-40 ECMWF 40 year re-analyses

ETOPO Global relief model of Earth's surface

FIMR Finnish Institute of Marine Research

FMI Finnish Meteorological Institute

GEBCO General Bathymetric Chart of the Oceans

GoB Gulf of Bothnia

GoF Gulf of Finland

GoR Gulf of Riga

HARMONIE A non-hydrostatic convection-permitting atmospheric model

HELCOM Helsinki Commission

HIRLAM High-resolution limited area model

HIROMB High-resolution operational model for the Baltic

HZG Helmholtz-Zentrum Geesthacht (Germany)

IOW Leibniz Institute for Baltic Sea Research Warnemünde (Germany)

LES Large Eddy Simulations

MSFD Marine Strategy Framework Directive

MSI Marine Systems Institute, Estonia

NBP Northern Baltic Proper

NCAR National Center for Atmospheric Prediction

NCEP National Centers for Environmental Predictions

NERI National Environmental Research Institute, Denmark

NWP Numerical Weather Prediction

SMHI Swedish Meteorological and Hydrological Institute, Sweden

RCA Rossby Centre regional atmospheric climate model

SOLAS The international convention for the Safety of Life at Sea

SST Sea surface temperature

SYKE Finnish Environmental Institute

UNESCO United Nations Educational, Scientific and Cultural Organization

WAM WAve Model

WFD Water Framework Directive

XNL Exact solution of the non-linear four-wave interactions

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